STUDYING THE PHOTOELECTRIC EFFECT AND DETERMINING PLANCK'S CONSTANT

1. The aim of the laboratory

To observe the photoelectric effect on a metal surface under light with different wavelengths and to determine the value of Planck's constant.

2. Theoretical approach

While studying the characteristics of the radiation originating from oscillatory discharges, H. Hertz observed that a spark discharge occurred more readily between two charged spheres when they were illuminated by another spark discharge. At about the same time, other physicists found that negatively charged Zn plates became discharged when illuminated by the UV radiations from an arc lamp. Positively charged plates did not loose their charge when were illuminated with the same radiation. The systematic study of the peculiar effects that the UV radiation has on metal surfaces led to the discovery of the photoelectric effect, a phenomenon that defied explanation based on the electromagnetic wave theory of light. The results of these experiments imply that the the light impacting on the Zn plates causes it to loose electrons. The German physicist Philipp Lennard (1862-1947) published the results of the first quantitative studies of the photoelectric phenomenon, in 1902. By measuring the charge-to-mass ratio of the negative electricity derived from an Al plate illuminated by UV light, he proved that electrons were ejected from the metal surface. They are called photoelectrons. Subsequent investigations have shown that all the materials exhibit photoemission of electrons. The photoelectric effect consists of the emission of electrons by a substance when illuminated by electromagnetic radiation. Einstein was the one who saw in the photoelectric effect the confirmation of the dual (wave and corpuscle) character of light, recognized by the modern interpretation of light: radiant energy is transported by photons that are guided along their path by a wave field.

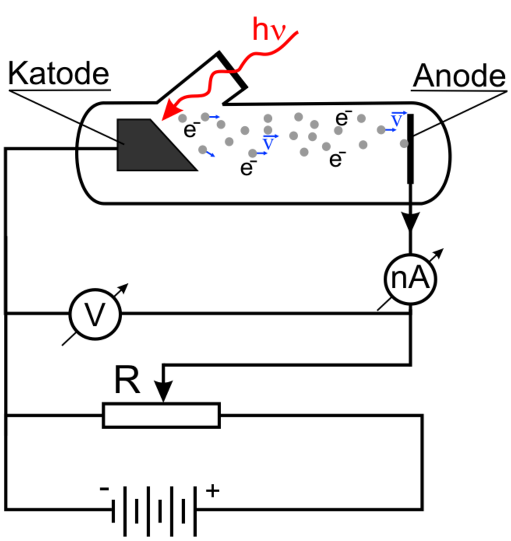

Figure. 1.

Figure 1 shows an apparatus used to study the photoelectric effect. Monochromatic light, falling on the metal plate K (the cathode), made of a photosensitive metal (Rb, Cs, Zn, etc.), will release photoelectrons that will be detected as a small current (nA), closing the circuit between the two electrodes. A potential difference U is applied between the cathode (K) and the anode (A); it can be varied and reversed in sign by a switching arrangement not shown in the figure. A galvanometer G serves to

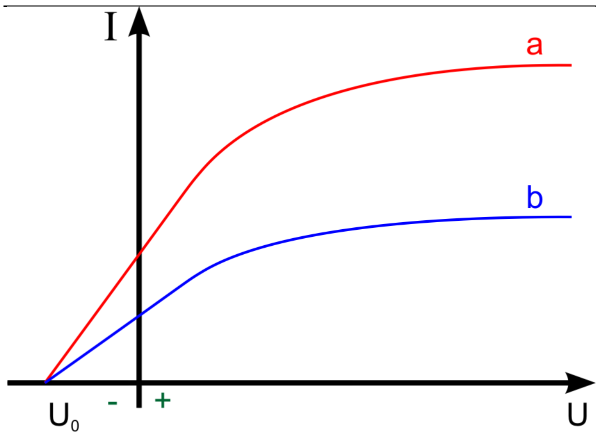

Figure 2

measure the small photoelectric current. Figure 2 is a plot of the photoelectric current as a function of the potential difference U. If U is made large enough, the photoelectric current reaches a certain limit at which all the photoelectrons ejected from the surface K are collected by the anode A. If U is reversed in sign and the cathode K becomes positive, the electrons released by photoelectric effect will experience a potential barrier. Though, the photoelectric current does not immediately drop to zero. This proves that the electrons are emitted from K with a finite velocity. Some electrons will reach the electrode A, in spite of the fact that the electric field opposes their motion. However, if this reversed potential difference is made large enough, a value U_0 (called the stopping potential) is reached at which the photoelectron current becomes null. This potential difference U_0 multiplied by the electron charge, measures the kinetic energy K_{max} of the fastest photoelectron ejected from the metal plate:

$$K_{max} = eU_0 \tag{1}$$

were K_{max} turns out to be independent on the intensity of light as shown by the curves *a* and *b* in figure 2. The two curves were drawn for two different intensities of light, and they cross the voltage axis at the same value U_0, if they have both the same wavelength (or frequency).

Figure 3 shows the stopping potential U_0 as a function of the frequency of the incident light, for a Na surface. On the graph it appears that there is a definite cutoff frequency, below which no photoelectric effect occurs. These data were taken by R. A. Millikan (1868-1953) whose work on the photoelectric effect won him the Nobel prize in 1923. Because the photoelectric effect is largely a surface phenomenon, it is necessary to avoid oxide films, grease, or other surface contaminants. He succeeded to devise a technique able to cut shavings from the metal surface under vacuum conditions. The wave theory serves well in the explanation of radiation transmission phenomena. And yet, three major features of the photoelectric effect cannot be explained in terms of the wave theory of light:

1. Wave theory suggests that the kinetic energy of the photo-electrons should increase as the light beam becomes more intense. However, fig. 2 shows that $K_{max} = eU_0$ is independent of the light intensity.
2. According to the wave theory, the photoelectric effect should occur for any frequency of light, provided that it is only intense enough. However, fig. 3

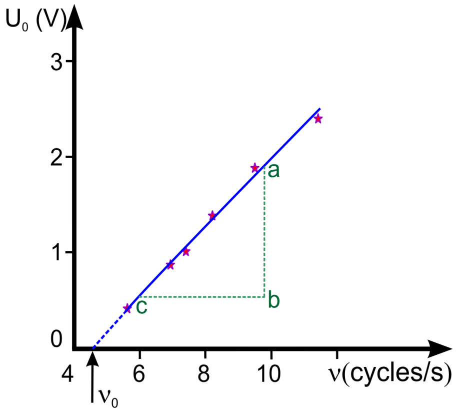

Figure 3.

shows that for each material surface there is a characteristic cutoff frequency ν_0. For frequencies less than this, the photoelectric effect canot be produced, no matter how intense the light is.

3. If the light is feeble enough, there should be a measurable time lag between the impinging of the light on the surface and the ejection of a photoelectron. During this interval the electron should be "soaking up" energy from the beam until it had accumulated enough energy to escape. However, no detectable time lag was measured.

Albert Einstein was the one who recognized the value of Planck's quantum hypothesis (that was published in 1901) in connection with the photoelectric effect. He reasoned that since the emission and absorption of light radiation occur discontinuously, certainly the transmission field should be discontinuous. In 1905, Einstein published a straightforward explanation of the photoelectric effect. It firmly proved the quantum theory: the transfer of energy between light radiation and matter occurs in discrete units called light quanta (or photons), the magnitude of which depends on the frequency of the radiation. The energy of a single photon is given by the equation: $E = h\nu$. Applying the photon concept to the photoelectric effect, Einstein wrote:

$$h\nu = E_0 + K_{max} \tag{2}$$

here $h\nu$ is the energy of the photon which carries this energy into the surface. Part of this energy (E_0) is used in getting the electron pass through the metal surface. The excess energy ($h\nu$ - E_0) is given to the electron in the form of kinetic energy. K_{max} represents the maximum kinetic energy that the photoelectron can have outside the surface. In nearly all cases, it will have less than this, because of losses by internal collisions. Einstein's photon hypothesis gives an answer to each of the three objections above, raised against the wave theory interpretation of the photoelectric effect:

1. There is complete agreement of the photon theory with the experiment. Doubling the light intensity merely doubles the number of photons and thus doubles the photoelectric current.
2. From eq. (2), if the maximum kinetic energy K_{max} equals zero, we have:

$$h\nu_0 = E_0 \tag{3}$$

In which case, the photon has just enough energy to get the photoelectrons out of the metal surface, and there is nothing left as kinetic energy. The quantity E_0 is called the *work function* of the substance. If the radiation frequency ν drops below ν_0, no matter how many photons are shined on the cathode (i.e. no matter how intense the illumination), they will not have enough energy to eject photoelectrons from the metal surface.

3. The explanation follows from the photon theory because the required energy is supplied in a concentrated bundle. It is not spread uniformly over a large area, as in the wave theory.

All the experiments led to the following conclusions known as the laws of the photoelectric effect:

1. There is a threshold value for the light frequency (the cut-off frequency) f_0 below which the effect cannot be produced.
2. The kinetic energy of the electrons released by photoelectric effect depends on the frequency of the incident light and does not depend on the light intensity.
3. The number of the photoelectrons emitted during the unit time, and hence the photoelectric current intensity, only depends on the intensity of the light and does not depend on its frequency.

Let us rewrite Einstein's equation (2) for the photoelectric effect, by substituting the product eU_0 for K_{max}. This yields, after rearrangements:

$$U_0 = \frac{h}{e}\nu - \frac{E_0}{e} \tag{4}$$

Thus, Einstein's theory predicts a linear relationship between the cutoff voltage U_0 and the radiation frequency ν, in complete agreement with the experimental results (see fig. 3). The slope of the experimental curve in this figure will be:

$$\frac{h}{e} = \frac{(22 - 0.65)V}{(10\cdot 10^{14} - 6\cdot 10^{14})\text{cycles/s}} = 3.9\cdot 10^{-15}\,\text{Vs} \tag{5}$$

We can thus find Planck's constant by solving the equation (5) for h:

$$h = 3.9\cdot 10^{-15}\,\text{Vs} \times 1.6\cdot 10^{-19}\,\text{C} = 6.2\cdot 10^{-34}\,\text{Js} \tag{6}$$

From a more careful analysis of this and of other data, on Li surfaces, R. Millikan found the value $h = 6.57\cdot 10^{-34}\,\text{Js}$, with an accuracy of about 0.5 %. This agreement with the value derived from Planck's radiation formula is a striking confirmation of Einstein's *photon* concept in explaining the photoelectric effect.

During this laboratory work, a different method will be used to find the value of Planck's constant *h*. If we write Einstein's equation of the photoelectric effect for two different wavelengths (and frequencies) of monochromatic light:

$$\begin{aligned} h\nu_1 &= E_0 + eU_0 \quad (*) \\ h\nu_2 &= E_0 + eU_0 \quad (**) \end{aligned}, \tag{7}$$

and if we subtract the second equation (**) from the first one (*), then we obtain:

$$h \cdot (\nu_1 - \nu_2) = e \cdot (U_{01} - U_{02}) \tag{8}$$

or else:

$$h = \frac{e \cdot (U_{01} - U_{02})}{\nu_1 - \nu_2} \tag{9}$$

Finally considering that $\nu = c/\lambda$, we get:

$$h = \frac{e \cdot \lambda_1 \lambda_2}{c(\lambda_2 - \lambda_1)}(U_{01} - U_{02}) \tag{10}$$

3. Applications

The photoelectric effect, additional to the fundamental role had in the confirmation of corpuscular theory of light, also has numerous practical applications. Anti-theft alarms and automatic door opening systems often use electric circuits with photoelectric cells. When a person breaks the light ray and the photoelectric cell is not radiated, the instantaneous canceling of electrical current acts on a switch that activates a buzzer or a door. Sometimes for alarms, the ultraviolet (UV) or infrared (IR) radiations are used because these are invisible for the human eye. Vice-versa, the photoelectric cell can also be used as an optical barrier with multiple rays, at protection systems and alarms or in the automatic opening or closing of doors in halls and garages. Many smoke detectors use photoelectric cells to detect infinitesimal amounts of smoke that breaks the light flux leading to a detectable decay of the electric current. One can also mention the use of photoelectric cells as photo amplifiers used in various detectors of α, β, γ or X-ray radiations. The photoelectric cells, photo-resistances, various photo-sensors, represent diverse applications of the external photoelectric effect. Note that, the photovoltaic (PV) panels used quite often in the last years to generate electric currents based on sunlight, imply a different type of phenomenon that takes place in semiconductors, and is called an internal photoelectric effect.

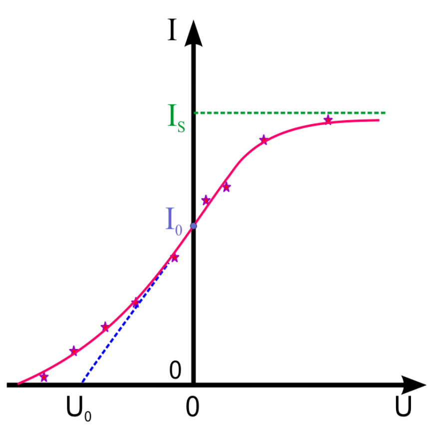

Figure 4.

4. Experimental Procedure

The purpose of this laboratory work is to observe the photoelectric effect, on a Cs cathode and to determine the value of the Planck's constant, *h*. Figure 1 shows the electrical circuit used to study the photoelectric effect. The photocell is provided with a Cs cathode-K and is supplied by a d.c. potentiometer device. The optical filters used allow the passing of monochromatic light with wavelengths: λ_1=6250Å (yellow) and λ_2=6896Å (red).

1. Plug in the galvanometer device, observing the appearance of the light spot on its scale. One of its divisions is equal to $9x10^{-9}$ A.
2. Supply the light source and introduce the filter nr. 1 (selecting light of wavelength λ_1) between the source and the electrodes.
3. Increase the positive voltage and record some values of the photocurrent intensity (in scale units) at various voltage values.
4. Swap the voltage bias, subsequently increasing the negative voltage, until the galvanometer indicates no current. Record the increasing values of the negative voltage and of the current, as it drops to zero.
5. These data will be used to plot the dependence of the photocurrent intensity versus the negative and positive voltage applied on the photocell, as shown in figure 4. A tangent drawn to extrapolate the linear region of the curve, as indicated, will point the stopping voltage for the first wavelength (U_{01}).
6. Repeat all the operations (2)-(5) with the second light filter. Thus, U_{02} will be determined.
7. Calculate Planck's constant, considering $e=1.6x10^{19}$ C and $c=3x10^{8}$ m/s, the accepted values for the charge of the electron and for the speed of light, respectively.
8. Finally calculate the relative deviations:

$$\frac{\Delta h}{h} = \gamma \cdot \frac{U_{max}}{U_{01} - U_{02}} \quad (\%)$$

Table 1

λ_1 6250 Å	U(V)	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
	I(div.)								25					
λ_2 6896 Å	U(V)	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5
	I(div.)								15					