Warsaw University of Technology
Faculty of Physics
Physics Laboratory I „P"
Jerzy Filipowicz

36

PHOTOELECTRIC EFFECT

1. Fundamentals

The photoelectric effect is one of the interactions between the electromagnetic wave, thus the light, and the matter. In this phenomenon electrons are emitted from a metal surface when the light (with an appropriate frequency) shines on it.

Investigation of this phenomenon took significant role in exploring the physics laws ruling the micro-world and contributed to create quantum physics in the beginning of the 20-th century.

H.G.Hertz in 1887 and P.Leonard in 1899 as the first scientists proved that the light can cause electrons emission from metals. Since then this phenomenon - called later the photoelectric effect - was investigated in detail, because a number of features of the photoelectric effect could not be explained on the basis of classical physics. Attempts to explain this phenomenon required changing an approach to the nature of the light which has been treated as electromagnetic wave.

The aim of this experiment is to explore fundamental properties of the photoelectric effect and to evaluate **Planck's constant**, a very important value in quantum physics.

1.1 Photoelectric effect description

In the investigation of the photoelectric effect we use photocell - the glass vacuum bulb with two electrodes. One of the electrodes - called photocathode - is prepared as a thin film of the metal, and the second one - called the collector electrode or anode - can be formed as a ring made from thin metal wire.
The experimental setup for photoelectric effect investigation is presented in fig. 1.

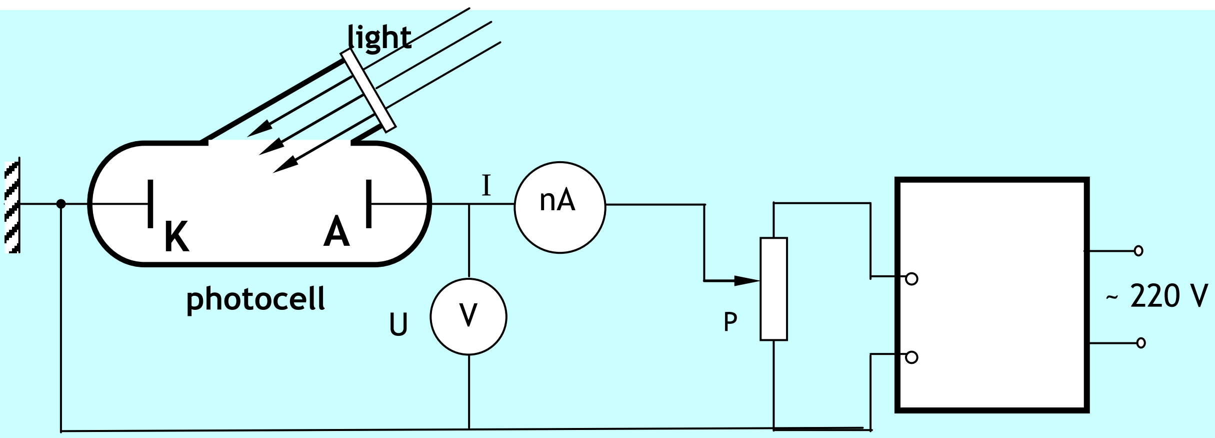

Fig. 1 Measurement setup: K- cathode, A - anode, P - potentiometer, U - voltage measured using voltmeter V, I - current measured using nanoammeter nA.

The glass used to fabricate photocell must be transparent for the light (visible and ultraviolet) which intensity and frequency can be changed. The voltage U between cathode and anode can be regulated using potentiometer P. The current flowing between electrodes can be measured using ammeter nA.

When the positive voltage is applied to the anode (respect to the photocathode) and in the absence of the photocathode illumination, there is no current flow in the circuit. The current starts to flow immediately after the photocathode is illuminated by the light with the high frequency.

Increasing of the positive potential of the anode causes initially linear increasing of the current, but from the certain value of the voltage U the current is saturated and its value is not changing anymore.

If in the same light condition the anode polarization would be changed into negative, making the voltage more negative, the decreasing of the current is near linear. From the certain voltage value V_h called **stopping voltage** the current is equal to zero (fig. 2a). The current-voltage characteristics made under the stronger illumination ($\Phi_2 > \Phi_1$) shows faster growth of the current and higher saturation current but the stopping voltage remains the same. When the frequency of the shining light changes and the intensity of the light Φ is the same (fig. 2b), the photoelectric current vanishes for different stopping voltages and for the certain light frequency (dependant on the photocathode material) the photoelectric effect does not occur at all. This frequency is called **the threshold frequency** ν_0. The corresponding light wavelength is called threshold wavelength λ_0 ($\lambda = c/\nu_0$). For the wavelengths bigger then λ_0 (frequency smaller then ν_0) electrons are not emitted.

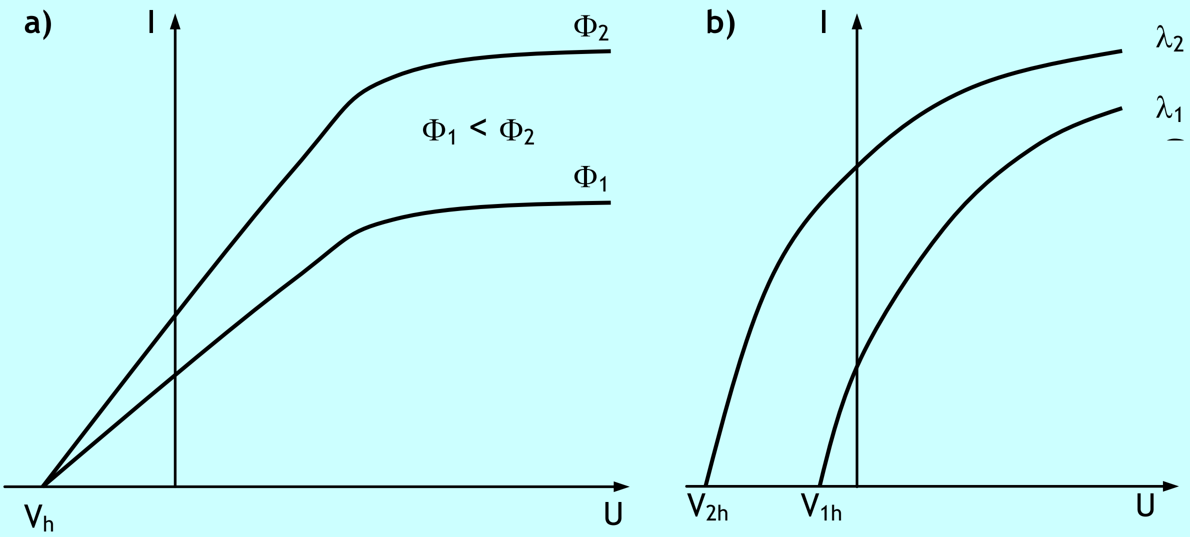

Fig. 2 Current-voltage characteristics of the photocell:
a) for two different light intensities Φ_1 i Φ_2 (V_h is the stopping voltage)
b) for two different wavelengths of the light shining on the photocathode.

The fraction of the energy which the emitted electron gets from the light must be used to overcome the work function W, and the rest can be changed into kinetic energy. The maximum kinetic energy $E_{max.}$ is equal to electric field work (between anode and cathode) needed to stop the electron:

$$E_{max.} = eV_h \quad \textbf{(1)}$$

where e denotes the charge of the electron.

So the experimental observations can be summarized as three main features:

1. **The stopping potential**, thus the maximum kinetic energy of the photoelectrons $E_{max.}$, **does not depend on the intensity of the light**. See fig. 2a and the equation (1).

2. **For the certain photocathode the characteristic threshold frequency ν_0 exists** (dependant on the cathode material). For **the frequencies smaller than ν_0 the photoelectric effect does not appear**, regardless of the intensity of the light and the prolongation of illumination.

3. There is no **delay in time** between the illumination of the photocathode and the moment when the photocurrent starts to flow, even for small intensities of the light.

1.2 Photoelectric effect interpretation

It is not possible to explain photoelectric effect on the basis of the wave concept of the light, because according to this theory **the energy of the wave depends on the intensity of the light (thus on the square of the wave magnitude)**. In such situation, the independence of the maximum kinetic energy of photoelectrons on the intensity of the light and the existence of the threshold frequency cannot be explained - for the high intensities of the light and the long times of illumination the effect should always occur. Similarly incomprehensive (from the wave theory point of view) is lack of delay between the photocathode illumination and photoelectron emission, because the electron should cumulate energy for some time until its energy would be sufficient to overcome the work function.

Interpretation of the photoelectric effect agreeable with experimental observations was created by **Albert Einstein in 1905. He proposed so called the photon (corpuscular) theory of the photoelectric effect**. According to this theory, the light must be treated as the collection of discrete packets of energy (**photons**). Each photon has energy $h\nu$, where h –Planck's constant, ν – frequency of the light. Taking such assumption, the photoelectric effect is the collision of two particles: photon and electron in the material. For such collision Einstein wrote the conservation-of-energy principle:

$$h\nu = W + E_{max.} \qquad \textbf{(2)}$$

where $h\nu$ - is **the photon energy** incident on the photocathode, W – **work function**, $E_{max.}$ – is **maximum kinetic energy of the ejected electron**. Mostly, the electrons will have smaller energy than E_{max} as the result of the interactions in the material.

The photon concept of the light provide explanation for all features of the photoelectric effect:

1. **Independence of the $E_{max.}$ on the light intensity** results from the fact that increasing light intensity increases the number of the photons, not their energy, and the energy $E_{max.}$ depends only on the energy of the single photon $h\nu$ (equation (2)).
2. **Existence of the threshold frequency** results from the fact, that photon energy needed to create photoelectric effect must be at least equal to the work function, so $h\nu_0 \geq W$ and photons having the smaller energy cannot eject electron from the material.
3. **Lack of the delay** results directly from the photon theory, because energy is supplied in finite packets instantaneously.

If we rewrite the equation (2) substituting $E_{max.}$ by eV_h from the equation (1), we obtain:

$$V_h = \frac{h}{e}\nu - \frac{W}{e}\,. \qquad \textbf{(3)}$$

So the Einstein's theory foresees linear dependence between the stopping potential V_h and the frequency of the incident light ν what is perfectly consistent with experimental results (fig. 3).

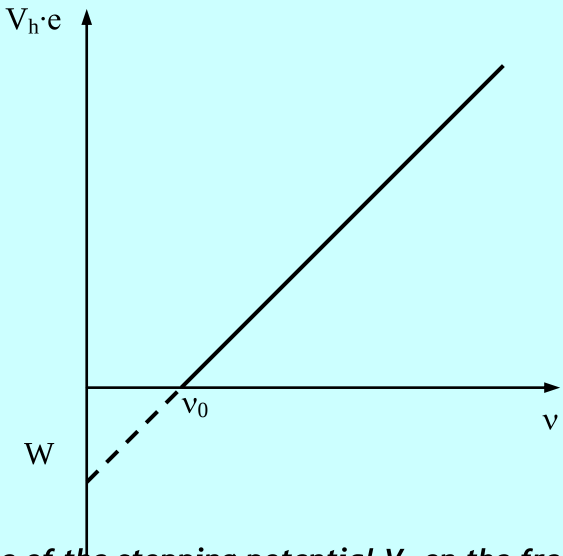

Fig. 3. Dependence of the stopping potential V_h on the frequency ν of incident light. (ν_o is the frequency threshold characteristic for certain material of the photocathode and W is the work function).

The line $y = bx + a$ where $y = V_h \cdot e$, $x = \nu$, $b = h$, $a = W$ presented in the fig. 3 and knowledge of the electron charge e allow to compute the Planck's constant (slope value b) and the work function W (intersection value a). The evaluation of the Planck's constant is one of the main goals of this experiment.

1.3. Wave - particle duality

The success of the corpuscular theory of the light in the photoelectric effect explanation creates the fundamental question: **What is the light: wave or the collection of particles - photons?** We know that light (as every wave) exhibit interference and diffraction effects, and from the other hand the phenomena such as photoelectric effect, Compton's effect and electron-positron creation show the particle-like behavior. In such situation one has to state that the light has wave-like features as well as particle-like ones. The nature of the light is the composition of these features causing the light acts like the wave in some conditions and in the others like particle (photon) with energy $E = h\nu$ and momentum $p = h/\lambda$.

All material particles have the similar dual nature, what is described by the de Broglie hypothesis, whereby with every particle having the momentum p the certain wave can be associated. Its wavelength is $\lambda = h/p$, where h –Planck's constant. This hypothesis was confirmed by the experiments in which material particles (electrons) exhibited diffraction effects and acted wave-like.

In the recent years, due to construction of the high-energy light sources (high power lasers), it shows that the photoelectric effect using such light sources cannot be described by the equation (2). This is the result of the multiphoton interactions. When the density of the photons is very high, the electron can simultaneously interact with many photons and absorb their energy.

2. Description of the laboratory setup

The laboratory setup, which the principle of operation is presented in the fig. 1, consists of the photocell, the monochromator and the white light source or the set of the LED diodes, potentiometer for regulating supply voltage and it polarization and voltmeter and ammeter. The monochromator or LED diodes allow using light with the known wavelength λ.

3. Measurements

The way the measurements are carried out depends on the used laboratory setup. Detailed information can be found on the information plate.

4. Results

1. Using the least squares method calculate the slope of the line representing the Vh(ν) relation (equation 3). Calculate the Planck's constant and its uncertainty based on the slope value b. Basing on the intercept value a, find the work function and its uncertainty. NOTICE- **Use Origin software!**
2. Calculate expanded uncertainties of the both obtained values.
3. Compare obtained Planck's constant h with the official table of physical constants and comment on the used method.
4. Draw two obtained current-voltage characteristics on a common chart, marking the uncertainty bars. In the report comment on the obtained charts and compare them with the theory.

The physical constants:
c = 299792458 m/s **e = 1,60217733 x 10^{-19} C** **h = 6,6260755 x 10^{-34} Js**

5. References

1. Cutnell J. and Johnson K., Physics, 7th Edition, Wiley, 2007, Chapter 29
2. Halliday D., Resnick R., Walker J., Fundamentals of Physics, Six Edition, Wiley, 2001, Chapter 39
3. http://galileo.phys.virginia.edu/classes/252/photoelectric_effect.html