Exercise 91	INVESTIGATION OF EXTERNAL PHOTOELECTRIC EFFECT

Aim of the exercise

- Measurement of the spectral characteristics of the photocurrent ***i(λ)*** in the phototube (a kind of a photocell).
- Determination of the cutoff wavelength (related to the threshold frequency) of the external photoelectric effect.
- Determination of the work function of the metal the cathode in the phototube was made of.
- Calculation of the maximum kinetic energy of the electrons ejected from the cathode for a chosen wavelength.
- Measurement of the current-voltage characteristics *i(U)* of the phototube for two intensities of the incident light.

Issues: external photoelectric effect, phototube, work function, cutoff wavelength (or related threshold frequency).

1. Theoretical background

1.1. External photoelectric effect

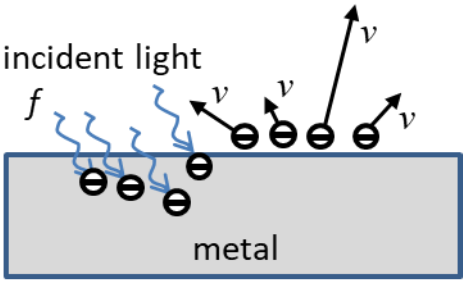

Fig. 1. The external photoelectric effect.

Light has a dual wave-particle nature. The external photoelectric effect reveals the particle (quantum) nature of light. In this approach the beam of light is quantized (divided) into particles called photons. Each photon has the energy $E_f = hf$ where f is the frequency of the light and h is the Planck's constant. The external photoelectric effect consists in the ejection of electrons out of the metals (or some other materials) under the influence of the incident light of a given frequency f (fig. 1). This effect was explained by Einstein who assumed that electrons do not interact with the whole beam of light but one electron interacts with one photon i.e. one electron absorbs one photon.

If the energy of photon is large enough the electron may escape from the metal. When the electron passes out through the metal surface, it must overcome an energy barrier W, called work function.

According to Einstein-Millikan equation the maximum kinetic energy E_{kmax} of the electron ejected from the metal by the photon is as follows:

$$E_{kmax} = h\cdot f - W \quad \text{so:} \quad E_{kmax} = h\cdot c/\lambda - W \,, \qquad (1),\ (2)$$

where:

h – Planck's constant,

f – the frequency of the incident light,

$h \cdot f$ – energy of photon,
c – speed of light,
λ – wavelength of the light,
W – work function i.e. the energy which electron loses while going out through the energy barrier at the surface of metal. It depends on the kind of the metal and the state of its surface (roughness, chemical state e.g. oxidation).

Not all of the ejected electrons have the maximum energy given by the eq. 1 and 2 but only those which have absorbed the photons being very close to the surface (just under). Those electrons which are deeper under the surface lose not only the energy associated with the energy barrier W at the surface but additionally lose some energy on their ways to the surface due to collisions with atoms and other electrons. So the minimum energy of photon necessary to begin the external photoelectric effect ($E_{k,max} = 0$) is equal to the work function W:

$$h \cdot f_o = W \quad \text{or} \quad h \cdot c/\lambda_o = W\,, \qquad (3), (4)$$

where:

f_o – is called the threshold frequency (or cutoff frequency) of the external photoelectric effect. It is the frequency of the incident light (or more generally, of the electromagnetic wave) below which the effect does not occur, no matter how intense the radiation of a given frequency is i.e. how many photons hit the metal.
λ_o – the cutoff wavelength of the process which corresponds to the threshold frequency ($\lambda_o = c/f_o$) . For longer wavelengths the photoelectric effect ceases.

1.2. Phototube. Photocurrent dependence on voltage.

The photoelectric effect can be applied in the phototube (fig. 2 and 3) which is built of a transparent tube with vacuum inside. The tube includes cathode and anode which are connected to the power supply as shown in the fig. 3. The dependence of the photocurrent (current induced by light) on the voltage (potential difference between anode and cathode) $i(U)$ in this circuit is presented in the graph (fig. 4). When the cathode is illuminated by the monochromatic light with its frequency f above the threshold frequency ($f > f_o$) the current can flow if the voltage U is above the stopping potential U_{stop} ($U > U_{stop}$). The stopping potential depends on the frequency of the light f and on the work function W of the metal the cathode was made of. Let's analyze the $i(U)$ dependence for two colors of monochromatic light: red and blue whose frequencies are higher than the threshold frequency.

Fig. 2. The photo of the phototube.

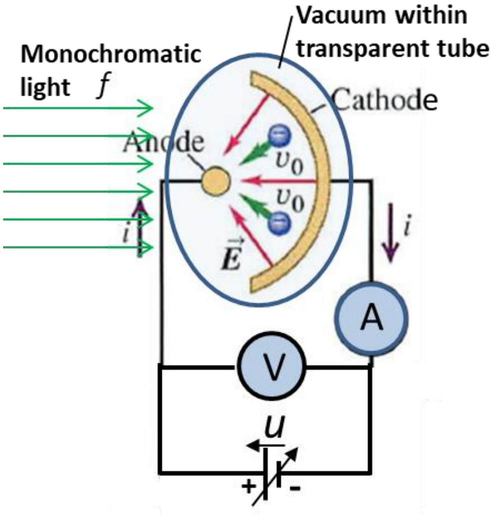

Fig. 3. Scheme of the phototube (Young and Freedman, University Physics 12th).

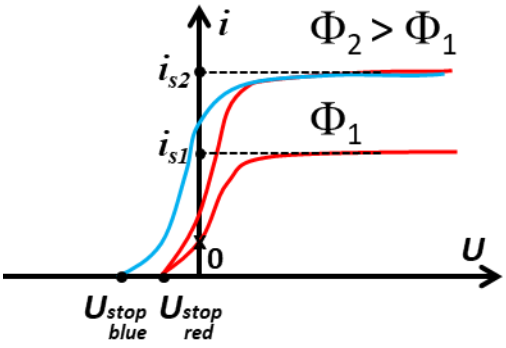

Fig. 3. Photocurrent vs voltage for a phototube.

First, let's analyze the red light of low intensity (see the red line denoted by **Φ_1**). It can be noticed that even for the voltage **$U = 0$** the current flows through the phototube (point **x**). It is due to the light which ejects electrons from the cathode with a certain kinetic energy. They are ejected randomly at different directions. Some of them are directed at the anode and they do not need any electric field to reach the anode. So the current is not equal to zero. The rest of the ejected electrons miss the anode. But if the voltage is applied with positive electric potential on the anode and gradually increased more and more electrons are attracted by the anode so the current increases. It is so until all electrons ejected from the cathode reach the anode and the current saturates reaching the value **i_{s1}** and does not increase any more. Let's return to the point **x** to analyze what happens when the reverse bias voltage increases (**+** on cathode and **-** on anode). We can notice that the current gradually decreases and reaches zero at the voltage **$U_{stop\ red}$** which is called the stopping potential (or voltage). We remember that at point **x** the current flows due to the electrons ejected from the cathode which from the very beginning are directed towards the anode. We also already know that the electrons move at different speeds. The stopping potential stops the fastest electrons whose kinetic energy is given by eq. 1. and 2. For these electrons we can write:

$$e\left|U_{stop}\right| = E_{k,max} \tag{5}$$

where: **e** is the absolute value of the charge of an electron.

The slower electrons ejected from the deeper parts of the cathode are gradually stopped by changing the reverse bias voltage from zero to the stopping potential **U_{stop}**.

Now let's analyses the red line denoted by **Φ_2** which corresponds to the red light but of the intensity **Φ_2** which is higher than **Φ_1**. The higher intensity and the same color of light means that the beam of light includes more photons per second so the beam ejects more electrons. That is why for **Φ_2** the current is bigger than for **Φ_1** and saturates reaching higher value **i_{s2}.** But the stopping potential is the same because the maximum kinetic energy of the ejected electrons depends on the frequency of the light (eq. 1) not on the number of photons in the beam.

The blue line on the graph corresponds to the situation in which the cathode is illuminated by the blue light i.e. the light of higher frequency than the frequency of the red light (**$f_{blue} > f_{red}$**). So now the maximum energy of the ejected electrons is higher than in the case of red light. This is the reason for which the absolute value of the stopping potential for blue light is bigger than for red light. Moreover we can notice that the saturated current is the same as for the red light of the intensity **Φ_2** which may mean (assuming the same efficiency of photons of the two colors) that the two beams include the same number of photons. Efficiency of 100% means that all incident photons eject electrons. However the efficiency is usually smaller and depends on the material of the cathode and the state of its surface and changes with the wavelength.

1.3. Phototube. Spectral dependence of the photocurrent.

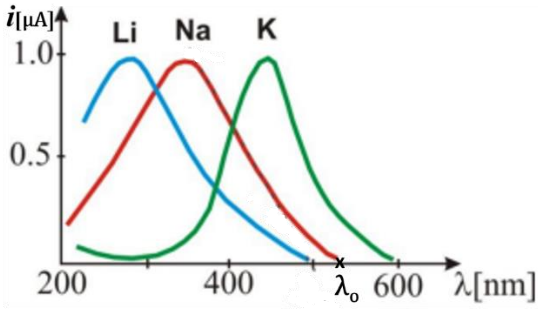

Fig. 4. Photocurrent vs wavelength for exemplary metals.

The graph in fig. 5 presents spectral dependences of photocurrent for cathodes made of different metals. It can be noticed that for wavelengths longer than a certain value $\boldsymbol{\lambda_o}$ (denoted for Na) the external photoelectric effect for the chosen cathode does not take place. The cutoff wavelength corresponds to the threshold frequency $\boldsymbol{\lambda_o = c/f_o}$. Having the wavelength and using equation 4 we can determine the work function ***W*** of the material the cathode is made of.

1.4. Phototube. Dependence of photocurrent on the intensity of light illuminating cathode.

The more photons illuminate the cathode the bigger is the number of ejected electrons from the cathode so bigger is the photocurrent. The dependence is linear (fig. 6) for each wavelength and for the whole radiation including all wavelengths as well. The proportional dependence of the photocurrent on the intensity of the whole radiation take place on condition that the spectral distribution of the radiation does not change.

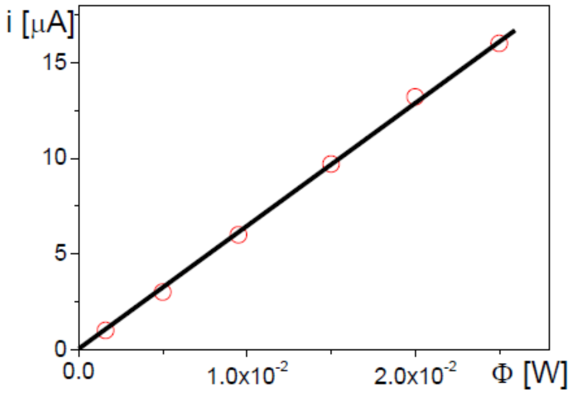

Fig. 6. Exemplary graph of photocurrent vs intensity of light.

1.5. Determination of the Planck's constant *h*.

Combining together equation 1 and 5 we can get the relationship between the measured absolute value of the stopping potential and the frequency of light illuminating the cathode:

$$|U_{stop}| = \frac{h}{e}f - \frac{W}{e}. \tag{6}$$

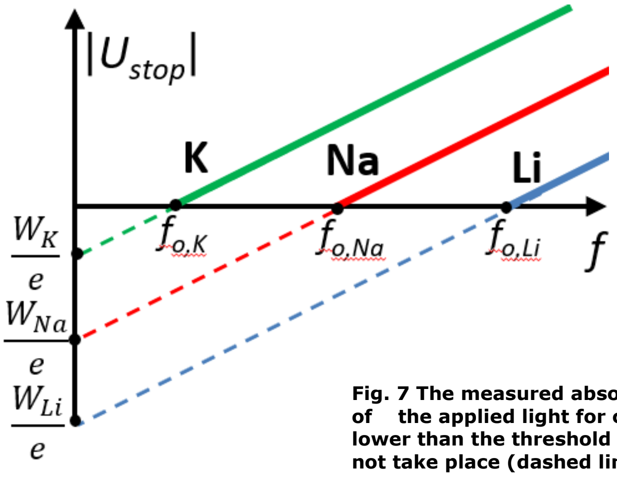

Fig. 7 The measured absolute value of the stopping potential vs the frequency of the applied light for cathodes made of different metals. For frequencies lower than the threshold frequency f_o the external photoelectric effect does not take place (dashed lines).

So Einstein's theory is consistent with experiments which show that the slope of the linear dependence is always the same regardless of the metal the cathode is made of. Getting the slope from the experiment and knowing that it equals ***h/e*** we can easily obtain the Planck's constant ***h***. So the external photoelectric effect applied in the phototube enables to determine very precisely one of the most important constants in physics. Moreover, the intersection of the straight dashed line with the vertical axis allows to calculate the work function ***W*** of the material the cathode was made of.

2. The measurement setup.

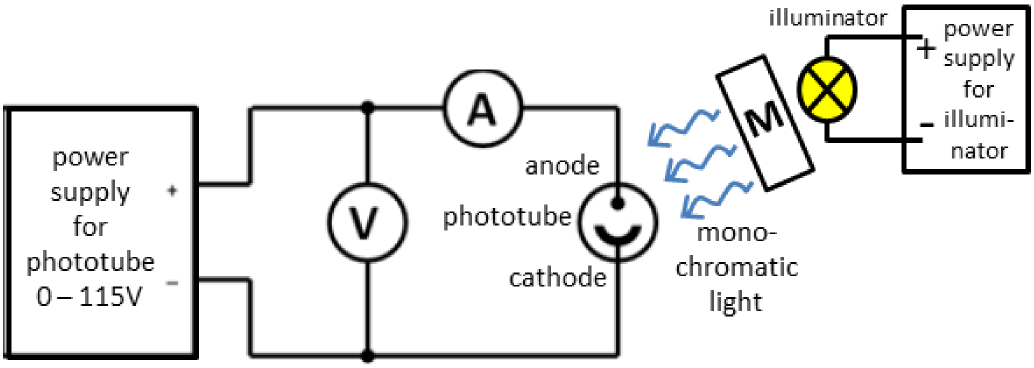

Fig. 8. Scheme of the measurement system.

The measurement system consists of the following components:

- phototube (with anode and cathode),
- power supply for the phototube (with the voltage regulation in the range 0 – 115V),
- illuminator with a monochromator **M** for selecting monochromatic light,
- power supply for the illuminator (with the switch for choosing one of two intensities of light),
- voltmeter,
- ammeter.

3. Measurements

3.1. Measurement of the spectral dependence of the photocurrent $i=f(\lambda)$.

Connect the power supply to the phototube (**+** to the anode and **−** to the cathode) and set the voltage to ***115V.*** Note the value of the dark current i.e. the current which is created as a result of thermal emission of electrons from the cathode and their emission by the scattered light entering the phototube from outside when the illuminator is turned off. Then switch on the illuminator (set to higher emission) and measure the spectral dependence of the photocurrent $i=f(\lambda)$ in the range from 370nm to 700nm every 5nm. Plot the graph presenting the $i=f(\lambda)$ dependence and read from it the cutoff wavelength λ_o. Then, using the equation 4, calculate the work function ***W*** of the metal the cathode was made of. For details, please refer to the manuals for this exercise.

3.2. Measurements of current-voltage characteristics ***i=f(U)***

a) Switch on the illuminator power supply and set it to higher illumination. Using the results obtained in the section 3.1. find the wavelength corresponding to the maximum value of the photocurrent and select this value in the monochromator. Connect the power supply to the phototube (**+** to the anode and **−** to the cathode). Measure the current-voltage dependence ***i=f(U)*** of the phototube in the range from 0 to 115V. Details should be found in the manuals.

b) Do the same measurements as in the point a) but for the lower intensity of illumination (the switch of the illuminator power supply set to down position).

c) Plot the results obtained in section a) and b) in the same system of coordinates and find out the saturation currents for both curves. Compare the results and draw the conclusions.

4. Do the analysis of uncertainties.

Some information about uncertainties can be found in the manuals.

5. Questions:

1. Write Einstein-Millikan equation and explain the external photoelectric effect.
2. Draw the scheme with the phototube for investigation of the external photoelectric effect.
3. Draw the graph presenting the dependence of the photocurrent on voltage ***i=f(U)*** for the phototube and explain it. Indicate the stopping potential and saturated current.
4. What does the stopping potential of the phototube depend on?
5. What does the saturated current of the phototube depend on?
6. Draw the exemplary spectral dependence of the photocurrent ***i=f(λ)***. Indicate the cutoff wavelength of the photo effect. What does the cutoff wavelength depend on?
7. Explain the method of determining Planck's constant based on the external photoelectric effect.
8. What is the work function and how to determine it? What does it depend on?

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References:

1. Young and Freedman, University Physics 12th.
2. https://lpf.wppt.pwr.edu.pl/