ATOMIC PHYSICS
PHOTOELECTRIC EFFECT
Practical 2
DETERMINATION OF PLANCK'S CONSTANT BY MEANS OF THE STOPPING POTENTIAL METHOD

1 Introduction

When the photon interacts with an electron in a substance, the law of conservation of energy holds. As a result of light absorption, the electron energy increases by an amount equal to the photon energy. If this change in energy exceeds the work function of the electron, a minimum thermodynamic work (energy) needed to remove an electron from the substance, then the electron can leave the substance and become free. Such an electron is called a photoelectron. For a photoelectron, we can write the law of conservation of energy as

$$\frac{m\upsilon_{max}^2}{2} = h\nu - W, \qquad (1)$$

where υ_{max} is the maximum velocity of the emitted electron; W is the work function of the given material; ν is the frequency of the absorbed light.

It can be seen from the equation (1) that the emission of an electron is only possible if the photon energy is greater than the work function. The minimum frequency of light ν_{min} at which a photoelectric effect is possible is called the threshold frequency of the photoelectric effect. The value of ν_{min} is found from the condition:

$$h\nu_{min} = W, \qquad (2)$$

At the frequency of light exceeding the threshold frequency, the photoelectrons have a certain velocity, which leads to a photocurrent flow through the photocell even at voltages at which the anode will have a negative potential with respect to the photocathode. Such a voltage is called the stopping potential, because it stops all the electrons from reaching the anode and, if their velocity is low, such electrons can return back to the cathode.

A typical IV curve of a vacuum photocell is shown in Fig. 1.

The stopping potential represented with a region of negative voltages on the IV curve. At a certain voltage, the photocurrent turns to zero.

The value of the stopping potential satisfies the following condition

$$\frac{m\upsilon_{max}^2}{2} = eV_0, \qquad (3)$$

which, together with the Einstein equation for this case, gives

$$V_0 = \frac{h\nu}{e} - \frac{W}{e}, \qquad (4)$$

The graph of the dependence of V_0 on the frequency of the light incident on the photocathode is shown in Fig. 1. From this graph it is possible to determine Planck's constant

$$h = e\frac{V_2 - V_1}{\nu_2 - \nu_1}, \qquad (5)$$

while the work function is computed as follows

$$W=e\frac{V_2\nu_1-V_1\nu_2}{\nu_2-\nu_1}, \qquad (6)$$

where V_1 and V_2 - are the stopping potentials corresponding to frequencies ν_1 and ν_2, respectively.

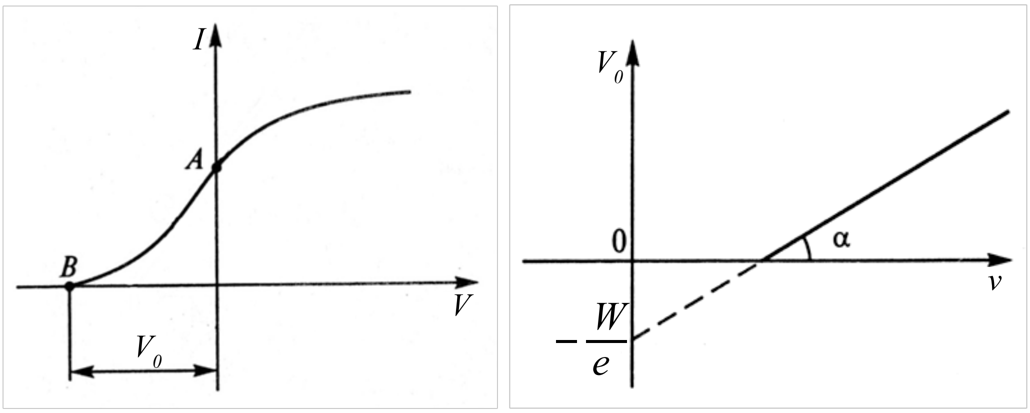

Fig. 1. Left: An IV curve of a vacuum photocell. Right: A stopping potential dependence on the frequency of the incident light.

2 Experimental setup

The vacuum photocell PC with an antimony-cesium alloy cathode is used in this practical. The electric schematic together with the general view of the setup is shown in Fig. 2. **Attention: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б" !!!**

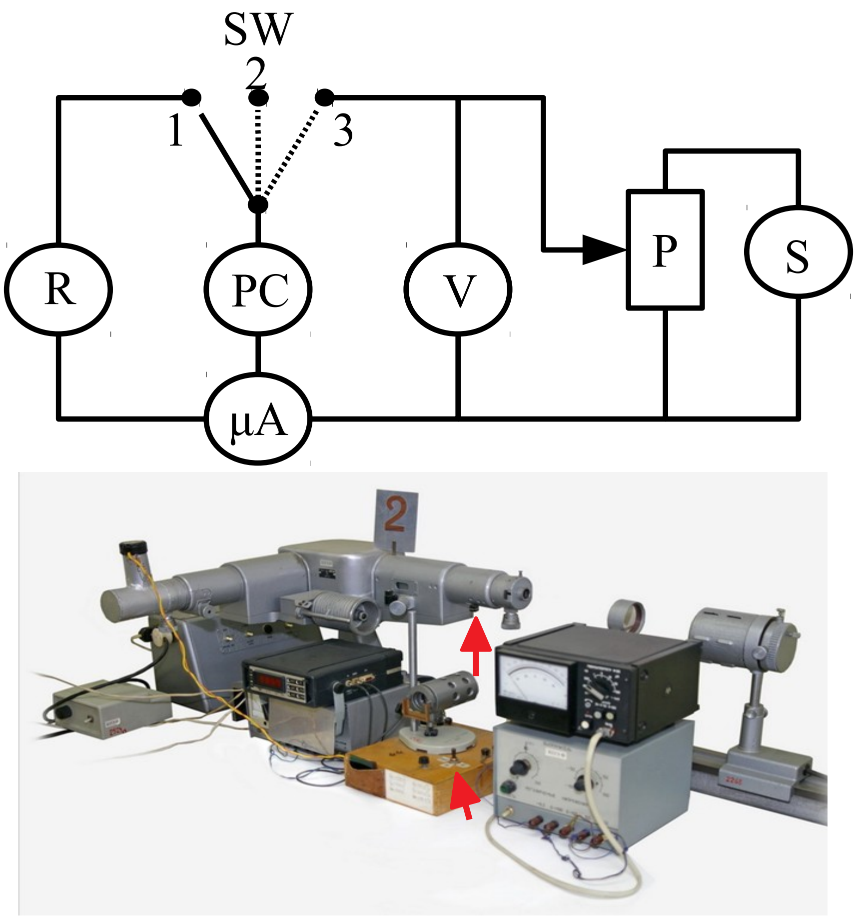

Fig. 2. An electric schematic and the general view of the setup.

To determine the threshold frequency of the photoelectric effect, place the photocell in the cartridge and insert into a special case at the output of the monochromator (Fig. 2). Keep the photocell parallel to the axis of the output arm of the monochromator. Shine white light from the filament lamp 1 (Fig. 3) through the condenser 2 to the input slit 3 of the monochromator 4.

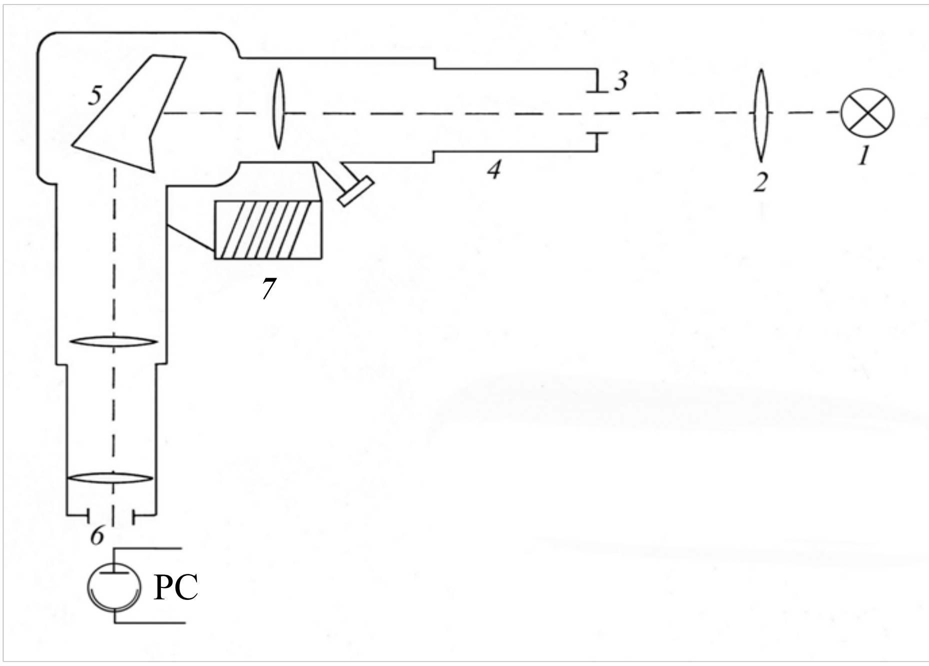

Fig. 3. The schematic the monochromator, which is used in the setup.

As a result of the dispersion of white light by the prism system 5 a relatively narrow spectral range passes through the output slit 6 of the monochromator, which forms an input light beam to the photocell PC. The width of the spectral range reaching the photocell is determined by the width of the output slit, which can be adjusted with a special screw.

Rotating the prism with the aid of the control 7 located in the middle part of the monochromator, it is possible to tune the part of the spectrum illuminating output slit and hence the photocell. The control is marked with degrees. The degrees correspond to wavelengths through the calibration curve that is attached to the monochromator.

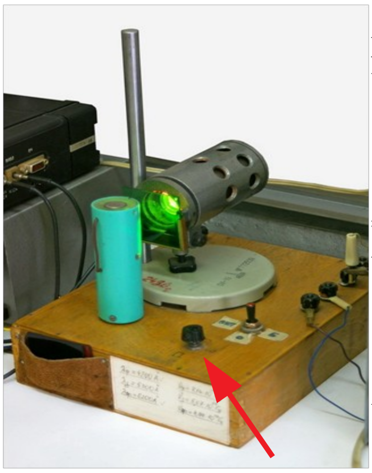

Fig. 4 The potentiometer knob location

To estimate the magnitude of Planck's constant, plot an IV curve of the photocell in the region of the stopping potential at two different frequencies of the incident light.

To do this, fix photocell on the panel opposite to the incandescent lamp (Fig.4). The lamp is equipped with a special holder for the filters which determine the frequency of the output light of the lamp. The filters (violet λ_{viol} = 0.42 μm, green λ_{gr} = 0.48 μm, orange λ_{or} = 0.62 μm) pass a relatively wide wavelength interval $\Delta\lambda / \lambda \approx 15\%$, so the wavelengths indicated on the filters can only be considered as the approximate values.

An ammeter Ф-195 is used to measure the anode current, while the stopping voltage is measured with a digital voltmeter B7-35. The digital voltmeter B7-35 measures voltage in the digital form and is equipped with an automatic selection system of the measurement limits. The stopping voltage on the photocell is supplied from the constant voltage source S (ИЭПП). The voltmeter and the source S are located right below the monochromator control 7 (see Fig. 1). The applied stopping voltage is regulated by the knob of the potentiometer P (indicated by the arrow Fig. 4).

3 Measurement and data processing

Task 1. Determining the threshold frequency of the photoelectric effect and calculating the work function.

1. Fix the photocell in the cartridge (mind the polarity) and place it inside the monochromator output arm (see Fig.2).

2. Check the initial position of the knobs on the instruments (in order to keep the instruments safe), which are used in the setup:

a) power supply R (ВУП): the initial position of the **voltage adjustment knob** "0-100" – far left position, which corresponds to 0 V;

b) ammeter Ф-195: the **RANGE button** is in the position "0-100"; switch the **range knob** to the position "100 nA";

c) the **control** of the monochromator is set to 1300°, which corresponds to the violet region of the spectrum;

d) the **light control knob** of the monochromator (indicated by the black arrow in Fig. 2) switch to the "CLOSED" position;

e) the **"SW" knob** (indicated by the red arrow in Fig.2) switch to the "2" position.(Notes: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б").

3. Turn on the ammeter Ф-195 by pressing the **On/Off button**. If everything is done right, red light will light up above the button. Allow the instrument to warm up for 10-15 minutes.

4. Switch the **"SW" knob** to the "1" position. (Notes: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б").

5. Turn on the rectifier R and set the operating voltage to 100 V.

6. Measure the dark current of the photocell by means of Ф-195. During the dark current measurements, one can switch the **range knob** to the position 50 nA.

7. ***Don't forget to switch the range knob to the initial position 500 nA before the actual measurements!!!***

8. Turn on the incandescent lamp K-12 located in front of the input slit of the monochromator. Turn on the **On/Off button** on the power supply of the lamp. Make sure that the light beam is focused on the input slit of the monochromator.

9. Set the **light control knob** to the "ОТКРЫТО" position. Remove the protective cover from the input slit of the monochromator. In this case, the ammeter Ф-195 will show the current flowing through the photocell (5-15 units of the ampmeter scale). At current values significantly lower than the dark current value, it is necessary to adjust the light flux incident on the input slit and the width of the input slit of the monochromator (adjustment operations are performed by the teacher assistant or teacher).

10. Rotate the monochromator control towards the increase of the φ divisions, every 50° put down the current I flowing through the photocell into the Table 1. (The rotation of the control toward the higher values of φ corresponds to an increase in the wavelength of the incident light). Measurements are taken until the ammeter pointer stops at the dark current value. Repeat the measurement several times at the dark current value. (For better accuracy in determination of the "stopping position" of the ammeter needle, after reaching the dark current, do several extra turns of the monochromator control, to check that the current value doesn't change. After the dark current values are found, it is necessary to start rotating the monochromator control in the direction of decreasing divisions, until the ammeter needle again starts moving). Note the position of the control φ^0_{stop} corresponds to $I = I_{dark}$. Estimate the measurement error.

Table 1.

φ^0	1300	1350	1400	1450	1500	...	...	...	2800
λ, Å									
I, nA									

From the value of φ^0_{stop}, determine the threshold wavelength of the photoeffect λ_{stop} (using the calibration curve attached to the setup).

11. After the measurements turn off all the instruments: switch the "SW" knob to the "2" position (Note: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б"); **turn off the power supply;** switch the range knob of the ammeter Ф-195 to the "1 μA" position; turn off the incandescent lamp K-12; set the light control knob to the "ЗАКРЫТО" position; put the protective cover on the input slot of the monochromator.

12. Plot out the dependence of the photocurrent I on the wavelength - the spectral characteristic of the photocell (using the calibration curve of the monochromator).

13. Calculate the work function of electrons from the antimony-cesium cathode of the photocell in electronvolts (eV) as follows $W = h\nu_{stop}$. Estimate the error of the calculated result.

Task 2. Recording of the IV curve of the photocell and evaluating Planck's constant.

1. take out the photocell from the arm of the monochromator and place it in the holder (Keep the photocell parallel to the lamp) in front of the incandescent light (Fig. 4).
2. Insert the orange filter (λ_{or} = 0.62 μm) into the filter holder in front of the light lamp.
3. Prepare the ammeter Ф-195 for operation:

a) the **RANGE button** in the "0 - 100" position;

b) the **range knob** switched to "500 nA";

4. Check the B7-35 voltmeter before the operation. The voltmeter should be set to **DC measurement mode** (**DC/AC/HF knob** switched to "▬" position, which corresponds to DC measurements; **V/mA/MΩ knob** to "**V** " position). Turn the instrument on with the "On/Off button" on the rear panel.
5. Turn on the stopping voltage source S (ИЭПП) with the "On/Off " button. If everything is done right, the signal lamp on the panel of the device should light up.
6. Put the potentiometer P knob (indicated by the arrow in Fig. 4) in the far right position, which corresponds to the "0 V" stopping potential.
7. Switch the **"SW" knob** to the "3" position. (Notes: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б").
8. Turn on the lamp (Fig. 4). Rotating the knob of the transformer that regulates the intensity of light, make sure that the pointer of the ammeter deviates from zero by 80 - 90 scale divisions.
9. Record the IV curve of the photocell in the region of the stopping potential (see Figure 2). To do this, slowly turning the knob P of the potentiometer, increase the applied stopping potential until the photocurrent drops to zero.
10. Repeat the same measurements for the violet light filter (λ_{voil} = 0.42 μm).

WARNING!!! While replacing the light filters, it is necessary to switch the electrical circuit to the "open" mode by putting the switch **"SW" knob** in the "2" position, in order to avoid the over range readings on the ammeter and its breakdown. (Notes: "SW - (ВУП-0-Б)" knob positions: 1 – "ВУП"; 2 — "0"; 3 — "Б").

11. Put down the readings from the voltmeter and ammeter into table 2. Pay special attention to the voltages, which correspond to the zero photocurrent at each frequency (point B in Fig. 1).

Table 2.

λ_{voil} = 0.42 μm															
V, V															
I, μA															
λ_{or} = 0.62 μm															
V, V															
I, μA															

12. After the measurements are completed, turn off **"SW" knob** in the "2" position. Turn off the lamp. Adjust the range knob of the ammeter Ф-195 to the "5 μA" position. Turn off the source S (ИЭПП) of the stopping potential. Turn **voltage adjustment knob** (see Fig. 4) to the far right position. Turn off the ammeter and the voltmeter with the **"On/Off " buttons**.

Task 3. Measured data processing.

1. Using the data from table 2, plot the IV curves, which correspond to two frequencies of the incident light.
2. Determine the stopping potential for the specified frequencies.

3. Estimate the value of Planck's constant in two ways:

a) calculate the value by the formula (5);

b) using the threshold frequency of light obtained in task 1 and one of the known values of the stopping potential.

4 Questions

1. What phenomenon is called the photoelectric effect?

2. How can one determine Planck's constant by the stopping-potential method? How is Einstein's equation used in this case?

3. Calculate the photon energies of the visible range in electron-volts. According to the table "Work function of electrons from metal", determine for which metals irradiated with visible light the photoelectric effect can be observed.

4. Draw theoretical curves of the dependence of the kinetic energy of emitted photoelectrons on the frequency of incident light for two different metals. Is it possible to test these relationships experimentally?

5. Can you specify the phenomenon opposite to the photoelectric effect?

6. What phenomenon is called the internal photoelectric effect? Where is it observed? In which spectral region is the threshold frequency of the internal photoelectric effect?

7. What relation connects the momentum of the photon with its wave vector?

8. See also the questions to practical 1 "Study of the photoelectric effect".

9. Make an electric schematic demonstrating operation (connection) of the photocell during the measurements (note the difference between the direct and inverse connection of the photocell).