Laboratory experiment

Study of the Photoelectric effect and "measurement" of the Planck constant

1.1 Task

1. Based on the measurement of the external photoelectric effect, determine the value of the Planck constant h.
2. Determine the threshold frequency and wavelength for the used phototube.
3. Determine the uncertainties of all the measured quantities.
4. Plot a graph of the maximum kinetic energy of photoelectrons as a function of the light frequency – $T_{\max} = f(\nu)$.
5. Measure the dependence of the photoelectric current on the value of the stopping voltage for three wavelengths.
6. In one graph, plot all three dependencies of the photoelectric current on the stopping voltage measured within the previous point.
7. Compare the value of the measured Planck constant with the tabulated value and evaluate the difference.
8. Conduct the measurement and corresponding calculations (points 1–7) for both the experimental set-ups installed in lab; plot both the dependencies$T_{\max} = f(\nu)$ in one graph. Points 5-6 are conducted only for the experimental set-up with spectral photometer Spekol.

1.2 Note

On 20 May 2019, a new definition of the SI system of units came into force. Along with this new definition, some physical constants have been fixed, including the Planck constant. The Planck constant now has the value

$$h = 6.626\,070\,15 \cdot 10^{-34}\,\mathrm{J\,s}. \tag{1.1}$$

This value is by definition exact, and the Planck constant need not be measured. So the actual goal of this lab experiment is not to measure the value of the Planck constant, but to test that the physical theory works, to learn some experimental techniques, and to try to process the measured data.

1.3 Theory

The explanation of the photoelectric effect (photoeffect) is one of the great achievements of the early days of quantum physics. To explain the photoeffect, the idea of an electromagnetic wave as a stream of photons forming energy quanta, is necessary. The photoeffect cannot be explained on the basis of the continuous propagation of electromagnetic wave energy, which follows from the classical physics (Maxwell's theory). The famous German physicist Albert Einstein published a theory for the photoeffect in metals in 1905. In 1922, he was awarded the Nobel Prize in Physics for the explanation of the photoeffect.

Electromagnetic radiation (a stream of photons) transfers its energy to the electrons in the metal when it strikes its surface. The energy of a photon is given by the product of its frequency ν and the Planck constant h, i.e., $E_\nu = h\nu$.

When a photon strikes an electron, all its energy is transferred to the electron. If the energy thus obtained is greater than the so-called work function ϕ (which is a property of the metal), the electron can escape from the illuminated surface by overcoming potential barrier and so-called photoemission occurs. If a collector electrode is placed against the illuminated metal, the emitted electrons can reach this electrode and create an electric current (photocurrent) in the external electrical circuit.

Being fermions, individual electrons in conducting materials occupy different energy levels. The electrons occupying the highest energy level, close to the Fermi energy level, need the least amount of energy (the work function) to be liberated. The electrons occupying lower energy levels require higher energy than the work function to be able to escape from the metal. The difference between the photon energy and the energy needed for liberating from the metal results in the electron's kinetic energy.

These considerations are summarized in Einstein's equation for the photoeffect

$$h\nu = \frac{1}{2} m v_{\mathrm{max}}^2 + \phi, \tag{1.2}$$

where $T_{\mathrm{max}} = m v_{\mathrm{max}}^2 / 2$ is the maximum kinetic energy of photoelectrons emitted from a material with work function ϕ illuminated with light with frequency ν. Here m is the electron mass and v_{max} is the maximum electron velocity.

The lowest frequency at which the photoeffect still occurs is called the *threshold frequency*. The corresponding largest wavelength is called the *threshold wavelength* λ_{m}. For most metals, it lies in the ultraviolet region, only for alkali metals it lies in the visible spectrum. The values for these metals[1] are given in Tab. 1.1.

Symbol	Element	ϕ [eV]	λ_{m} [nm]
Cs	caesium	1.93	642
Rb	rubidium	2.13	582
K	potassium	2.24	554
Na	sodium	2.28	544
Li	lithium	2.36	525
Ba	barium	2.52	492
Ce	cerium	2.84	437
Ca	calcium	2.96	419

Table 1.1: Work function and threshold wavelength for some metals.

1.3.1 External and internal photoeffect

The external photoeffect is used in photoemissive cells – phototubes. The phototube consists of a glass tube, which has a part of the inner surface covered with a thin layer of metal. This layer forms one electrode – the photocathode. The collector electrode – the anode – is formed by a thin wire, usually in the form of a loop inside the glass tube. The interior of the phototube is either evacuated or filled with an inert gas

[1] The work function also depends on surface impurities and its treatment.

at very low pressure. Within the external photoeffect, electrons are released into the surrounding space.

In contrast, within the internal photoeffect, electrons are released only inside the material, which increases its electrical conductivity. The internal photoeffect occurs in semiconductors (selenium, tellurium, copper oxide, gallium arsenide GaAs). It is used, e.g., in photoelectric energy converters (photometers, photovoltaic solar cells), in photoresistors, etc.

1.4 Determination of the Planck constant

The principle of the Planck constant measurement method is shown in Fig. 1.1. Monochromatic light of known wavelength λ from a source ZM is incident on a phototube F, which is connected in the circuit shown in Fig. 1.1. The circuit allows the measurement of electric current through the phototube and setting an adjustable voltage U_s between its electrodes.

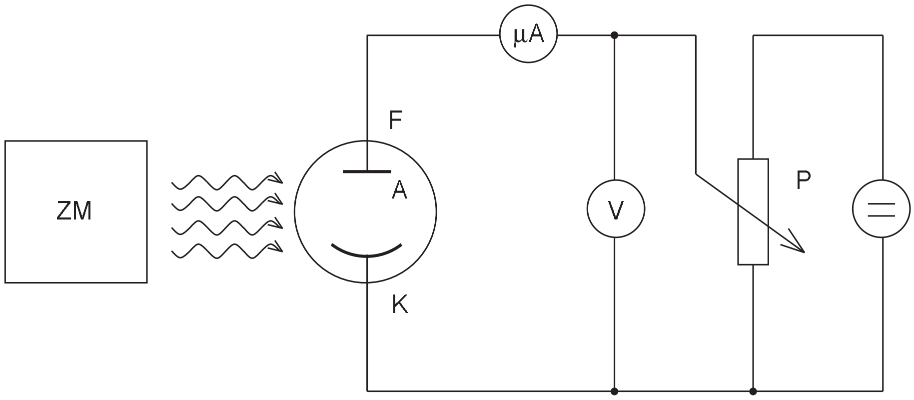

Figure 1.1: Experimental set-up. ZM – source of monochromatic light, F – phototube, V – voltmeter, μA – photocurrent meter, P – potentiometer.

The conditions of the experiment allow the photoemission to occur, as it is described by the relationship (1.2). For the determination of the Planck constant h, we also need to know the work function ϕ and the maximum kinetic energy of the emitted electrons $T_{\max}$.

The maximum kinetic energy of the emitted electrons can be measured–compensated by creating an electric field in the phototube which brakes the emitted electrons and thus the electric current through the phototube is zero.

In the compensated state, the maximum kinetic energy of the electrons is equal to the potential energy that stopped them, i.e.,

$$T_{\max} = \frac{1}{2} m v_{\max}^2 = eU_\mathrm{s}, \tag{1.3}$$

where U_s is the so-called stopping voltage (the potential difference for which the most energetic electrons have been stopped), and $e = 1.6022 \times 10^{-19}\,\mathrm{C}$ is the value of the electron charge. The stopping voltage is measured, so that the maximum kinetic energy $T_{\max}$ is this way determined.

However, this is not enough to determine the Planck constant, since we do not know what material the layer in the phototube is made of[2] (what is its work function ϕ). However, we can perform the compensation of the kinetic energy of the emitted electrons repeatedly for different wavelengths λ_i of the incident light.

[2]It can be shown that if the phototube electrodes are made of different materials, the measured work function is the one of the collector electrode – the anode.

1.4.1 Least squares method

For each of the different wavelengths λ_i we measure the corresponding maximum kinetic energy $T_{\mathrm{max}i}$ of the emitted electrons.

If we calculate frequencies of the incoming light as $\nu_i = c/\lambda_i$, where c is the light speed in vacuum[3], we obtain pairs $(\nu_i, T_{\mathrm{max}i})$, which should (in theory) lie on a straight line

$$T_{\mathrm{max}} = h\nu - \phi, \tag{1.4}$$

but, thanks to the existence of measurement errors, they are scattered in the vicinity of the theoretical prediction [Eq. (1.4)]. The estimate of the true values of h and ϕ is obtained by approximating the values $(\nu_i, T_{\mathrm{max}i})$ by the least squares method by a straight line (first degree polynomial) in the form

$$T_{\mathrm{max}} = a_1\nu + a_0. \tag{1.5}$$

If we use the kinetic energies $T_{\mathrm{max}i}$ in electronvolts[4] and the frequencies of the incoming light in petahertz[5], we get the estimate of the work function in electronvolts as

$$\phi = -a_0$$

and the estimate of the Planck constant in joule-seconds as

$$h = 1.6022 \times 10^{-34}\, a_1.$$

For the threshold frequency $T_{\mathrm{max}} = 0$, and from Eq. (1.5) it then follows

$$\nu_{\mathrm{m}} = -\frac{a_0}{a_1}.$$

For the calculation of the coefficients a_0, a_1, their uncertainties, and plotting the graphs, you can use the *Universal tool for plotting graphs* at webpage *https://planck.fel.cvut.cz/praktikum/*.

1.5 Procedure

To determine the Planck constant according to the above described method, two different types of experimental set-ups are available in the laboratory.

1.5.1 Experimental set-up with spectral photometer Spekol

Basic properties:

- Light bulb and diffraction-grating monochromator is used as a source of the monochromatic light.

[3] It holds (by definition) $c = 299\,792\,458\,\mathrm{m\,s^{-1}}$.

[4] One electronvolt is the kinetic energy that an electron gains (loses) in potential difference 1 volt, so that it holds $1\,\mathrm{eV} = 1.6022 \times 10^{-19}$ J. The numerical value of the maximum kinetic energy of the emitted electrons in electronvolts is therefore equal to the numerical value of the stopping voltage at which the photoelectric current drops to zero.

[5] It holds $1\,\mathrm{PHz} = 10^{15}$ Hz.

- The phototube is filled with gas, which introduces a systematic measurement error (bias). [6]
- A DC amplifier of Spekol together with an analog meter is used for measuring the current through the phototube.
- The source of the stopping voltage U_s is implemented as an external module connected to Spekol.

Detailed instructions for measuring with spectral photometer Spekol are given in Appendix 1.7 on page 6.

1.5.2 Experimental set-up with discharge lamp and monochromatic filters

Basic properties:

- The source of monochromatic light ZM is a mercury discharge lamp and a set of monochromatic filters placed on a carousel between the lamp and the phototube. The wavelengths of the filters are indicated on the carousel and correspond to some of the lines of the mercury lamp spectrum.
- The discharge lamp is housed in a lamp box with an output optics to allow optimum concentration of the light at the cathode of the phototube and is powered at 220 V mains via an inductor. The electrical circuit of the phototube is variant of the circuit shown in Fig. 1.1 and is schematically depicted on the set-up.
- Electric current through the phototube ($\sim 10^{-8}$ A) is converted by a built-in DC amplifier to a **voltage**, which is measured by an external **voltmeter**.
- Zero of the converter should be checked when the phototube is shielded (for this purpose there is one position designated on the carousel) and, unlike Spekol, cannot be adjusted. Zero-current compensation is done by considering the current flowing during the measurement through the phototube as zero, if the voltmeter reading is the same as that obtained with the shielded phototube.
- The set-up is equipped with a vacuum phototube designed specifically for the measurement of Planck constant. Usage of such a phototube is made possible by the sufficient intensity of the monochromatic light, provided by the discharge lamp and filters.

1.6 References

[1] Lego, J., Jelen, J.: Fyzika II. Praha, skriptum FEL ČVUT 1991.

[6] The phototube installed in the Spekol is designed to measure the optical transparency at low light intensities provided by the Spekol monochromator. For achieving higher sensitivity in the original working mode of the Spekol (with positive accelerating voltage at the anode), this phototube is filled with gas. When the Planck constant is measured (without the accelerating voltage) there is systematic error introduced in the measurement because the kinetic energy of the emitted electrons is reduced by collisions with gas molecules. Kinetic energy of the emitted electrons, as measured by the stopping voltage U_s is therefore less than the kinetic energy which the electrons have immediately after emission and its dependence on the frequency of the incident light is not exactly linear. The calculated value of h is thus always lower than its true value.

1.7 Appendix: Spectral photometer Spekol

The spectral photometer Spekol is designed to measure optical absorption and transmittance. Its schematic is shown in Fig. 1.2. Monochromator part of the instrument produces radiation in a narrow wavelength band 10 nm wide. The central wavelength of the band can be adjusted continuously. The light source is a light bulb Ž. The condenser C_1 together with the plane mirror Z focuses the beams onto the input slit of the monochromator S_1, located in the focal plane of the collimator lens C_2. The dispersion system of the monochromator is formed by reflection grating M. In the focal plane of the C_3 lens, a real image of the spectrum is formed from which the output slit S_2 selects a narrow spectral region around the desired wavelength.

Positions of slits and lenses are fixed, the desired wavelength is adjusted by rotating the grating about an axis parallel to the grating ridges. The rotation is carried out by means of a precisely-machined screw, the wavelength in nm can be read from the scale on a thimble. The slit width is set so that the bandwidth of the passband of the monochromator is approximately 10 nm.

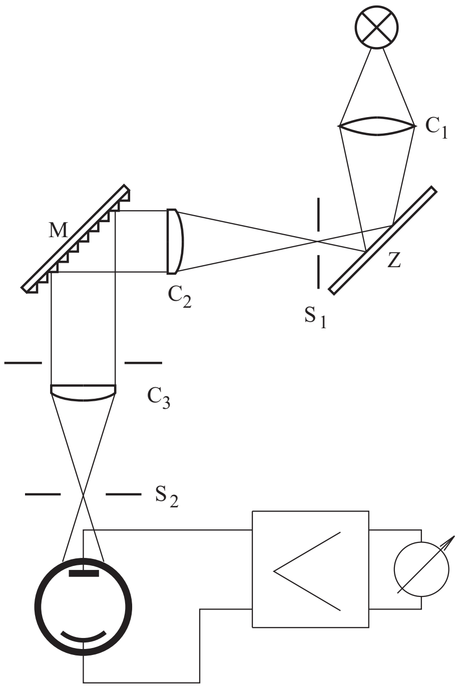

Figure 1.2: Schematic of spectral photometer Spekol.

The phototube is positioned in the path of the light coming out of the output slit. The phototube is connected via an amplifier with adjustable gain to an analog meter on the instrument panel (and also to an external module). In order to set the output of the DC amplifier to zero, the instrument is equipped with a shield that allows the light to the output slit to be blocked. The phototube then generates no current and zero value of the current indicated on the pfotocurrent meter can be set by a zero-potentiometer. Some versions of Spekol have the aperture-control lever with three positions: in addition to fully open or fully obstructed, there is a position that allows the output slit to be partially obstructed. Similarly, the control of the amplification is extended in some variants of Spekol by the possibility of stepped gain selection by a special rotary switch.

1.7.1 Measurement of the stopping voltage as a function of wavelength

1. Switch the photocurrent meter commutation to the position “normal” (control 1).

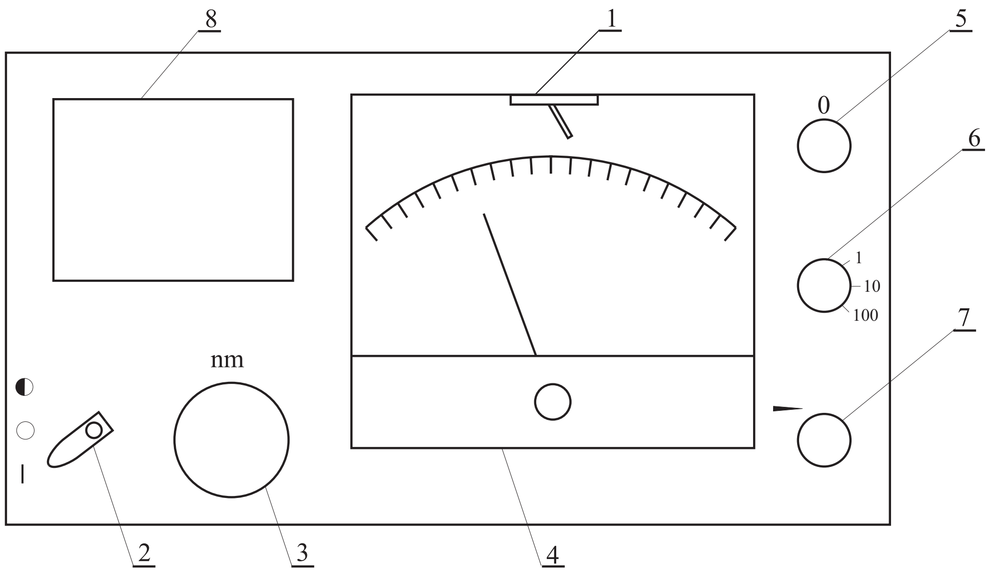

Figure 1.3: Controls of Spekol. 1 - photocurrent meter commutation switch, 2 - control of the output slit blockage, 3 - wavelength selection thimble, 4 - photocurrent meter, 5 - potentiometer for setting the amplifier output to zero, 6 - amplifier gain selection, 7 - potentiometer for fine gain adjustment, 8 - module with phototube.

2. Make sure that the stopping voltage source is switched off.
3. Switch on the light source with the switch on the Spekol power supply.
4. Block the output slit (control 2).
5. Set the light wavelength to 375 nm (control 3).
6. Set the amplifier gain to 100 (control 6).
7. Rotate the control for zeroing, until the photocurrent meter shows zero value (control 5).
8. Unblock the output slit (control 2).
9. Use the gain control to adjust the photocurrent meter pointer to 100 (control 7).
10. Switch on the stopping voltage source.
11. Increase the stopping voltage until the photocurrent meter on the Spekol reads zero. Record the value of the compensation voltage on the voltmeter.
12. Switch off the stopping voltage source.
13. Repeat steps 4 to 12 for another wavelength.

Perform the measurement for wavelengths 375 nm – 475 nm with step 25 nm. It is necessary to set the zero and the value of 100 shown by the photocurrent meter separately for each wavelength. In this way, the stopping voltage can be determined for each wavelength.

1.7.2 Measurement of the photocurrent as a function of stopping voltage

1. Switch the photocurrent meter commutation to the position "normal" (control 1). Make sure that the stopping voltage source is switched off. Switch on the light source with the switch on the Spekol power supply.

2. Block the output slit (control 2), set the required wavelength (control 3).

3. Set the amplifier gain selector to 100 (control 6).

4. Rotate the control for zeroing, until the photocurrent meter shows zero value (control 5).

5. Unblock the output slit (control 2).

6. Use the gain control to adjust the photocurrent meter pointer to 100 (control 7).

7. Switch on the stopping voltage source. Using the potentiometer on the stopping voltage module, adjust the photocurrent meter pointer to 100.

8. Read the value shown by the photocurrent meter and the stopping voltage shown by the voltmeter.

9. Using the potentiometer on the stopping voltage source, increase its value in order that the photocurrent "decreases by 10 graduations."

10. Repeat steps 2 – 9 until the photocurrent is zero.

Perform the measurement for three wavelengths in interval 375 nm – 475 nm. It is necessary to adjust the value of 0 and 100 on the photocurrent meter separately for each wavelength.