Laboratory exercise

External photoelectric effect

1.1 Measurement tasks

1. Measure the dependence of the maximum kinetic energy of electrons emitted in the external photoelectric effect on the frequency of the incident light. Compare the slope of this (linear) dependence with the Planck constant. Calculate the work function of the photocathode material and the corresponding threshold frequency.

2. For three wavelengths of the incident light, demonstrate that the maximum kinetic energy of the photoelectrons is independent of the light intensity.

3. For three wavelengths of the incident light, measure the dependence of the photocurrent on the potential difference between the cathode and anode of the phototube.

1.2 Theoretical background

Maxwell's theory of the electromagnetic field successfully explained the nature of light as an electromagnetic wave. The wave nature of light is confirmed by phenomena such as diffraction, interference and polarization.

Later experiments, however, showed that in phenomena such as absorption, emission or scattering, light does not behave as a wave but exhibits particle-like properties.

Today we know that the energy of electromagnetic radiation is quantized–it is emitted and absorbed in individual *packets* with a precisely defined energy. These quanta have a particle character and are called photons. Light (as well as other forms of electromagnetic radiation) exhibits so-called wave–particle duality: in some situations it behaves like a wave, in others like a stream of particles. Diffraction and interference are manifestations of wave-like behavior, whereas emission and absorption of photons testify to the particle-like nature of light.

1.2.1 Photoelectric effect

One of the phenomena that indicated the particle nature of light is the external photoelectric effect, in which a material illuminated by suitable light can emit electrons from its surface[1]. For an electron to escape from a given material, it must absorb enough energy from the incident light to overcome the attractive forces of the positively charged ions of the material's crystal lattice, which create a potential barrier for it.

[1] There is also an internal photoelectric effect, in which electrons do not leave the material but remain inside and become conduction electrons.

A schematic of a modern apparatus for studying the photoelectric effect is shown in Fig. 1.1. Here, a phototube consists of two electrodes inside a glass bulb from which the air has been evacuated. The electrodes are connected to a source of variable electric voltage, and one of the electrodes–the photocathode–is illuminated. Depending on the magnitude and polarity of the voltage U_{AC} between the electrodes, the electrons emitted from the photocathode may reach the anode and produce a photocurrent I_p in the external circuit.

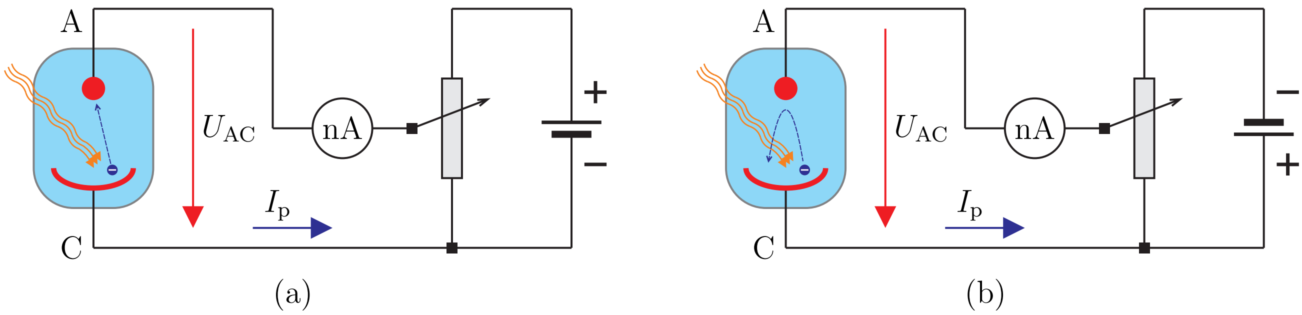

Figure 1.1: Schematic of the apparatus for investigating the external photoelectric effect.

The emitted photoelectrons have different kinetic energies. If the potential of the anode is higher than that of the photocathode, see Fig. 1.1(a), all photoelectrons are attracted to the anode and contribute to the photocurrent. Conversely, if the potential of the anode is lower than that of the photocathode, see Fig. 1.1(b), photoelectrons are repelled from the anode and those with low kinetic energy will not reach it. The maximum kinetic energy of the photoelectrons, $E_{k\,max}$, can be determined by setting the anode potential with respect to the photocathode to a sufficiently negative value $U_{AC} = -U_s$ such that the photocurrent in the external circuit just vanishes (no photoelectrons reach the anode). The voltage U_s is called the stopping voltage. Between the photocathode and the anode the potential drops by U_s, which means that the electrostatic field performs negative work on the electron, $W = qU_s = -eU_s$, where $q = -e$ is the electron charge and $e = 1.602\,176\,634 \cdot 10^{-19}\,\mathrm{C}$ is the elementary charge. Therefore, for the electrons with maximum kinetic energy we have

$$\Delta E_k = W \quad \Rightarrow \quad 0 - E_{k\,max} = -eU_s \quad \Rightarrow \quad E_{k\,max} = eU_s. \tag{1.1}$$

Hence, by measuring the stopping voltage we can determine the maximum kinetic energy of the photoelectrons emitted from the photocathode[2].

On the basis of these measurements one can conclude that absorption of light energy by the emitting surface and the subsequent emission of photoelectrons cannot be described by Maxwell's wave theory of light.

1.2.2 Predictions of Maxwell's wave theory of light

If the photoelectric effect were governed by Maxwell's wave theory of light, we could deduce the following predictions from that theory.

Prediction I: From Maxwell's equations it follows that for the intensity (of a plane progressive electromagnetic wave) in vacuum

$$I = \varepsilon_0 c E_{ef}^2, \tag{1.2}$$

[2]Within this text we ignore phenomena related to the fact that the photocathode and anode may be made of different materials.

where ε_0 is the electric constant (vacuum permittivity), $c = 299\,792\,458\,\mathrm{m\,s^{-1}}$ is the speed of light in vacuum, and E_{ef} is the effective value of the electric field intensity. According to (1.2) the light intensity does not depend on frequency, and therefore the photoelectric effect should occur for all frequencies and the magnitude of the photocurrent should not depend on light frequency.

Prediction II: As mentioned above, an electron leaving the photocathode must have a certain minimum energy to overcome the potential barrier (this minimum energy is called the work function and is a property of the electrode material). It should therefore take some time for the illuminated electrode surface to absorb enough energy to overcome the potential barrier. In other words, for a very weakly illuminated photocathode we expect a delay between switching on the light source and the emission of the first photoelectrons.

Prediction III: Because the energy absorbed by the photocathode surface depends on the light intensity, we expect the stopping voltage to increase with the light intensity. Since the light intensity does not depend on its frequency, we also expect the stopping voltage to be independent of frequency.

1.2.3 Experimentally established facts

Ingenious experiments performed by physicists at the end of the 19th and the beginning of the 20th century, however, yielded the following results.

Result I: The photocurrent depends on the light frequency. For a given material and monochromatic light there exists a threshold frequency below which the photoelectric effect does not occur, no matter how large the intensity of the incident light is.

Result II: If the light frequency is above the threshold for the photocathode material, there is no measurable delay between illuminating the photocathode and the emission of photoelectrons, even for arbitrarily low light intensity.

Result III: The stopping voltage does not depend on the light intensity, but it does depend on the light frequency. Figure 1.2 shows the dependence of the photocurrent I_{p} on the voltage U_{AC} between the phototube electrodes for two different intensities I_1 and I_2 of monochromatic light of the same frequency, with $I_2 > I_1$. The negative potential difference $-U_{\mathrm{S}}$ required to stop all photoelectrons is the same for both intensities. The intensity of the incident light affects only the number of photoelectrons emitted per unit time. For large positive potential differences U_{AC} saturation occurs–all photoelectrons reach the anode and contribute to the photocurrent.

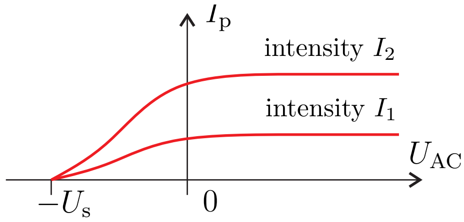

Figure 1.2: Volt–ampere characteristic of the phototube.

Experiments also show that if the light intensity is constant but its frequency increases, the magnitude of the stopping voltage increases. In other words, the higher the light frequency, the larger the maximum kinetic energy of the emitted photoelectrons.

1.2.4 Einstein's explanation of the photoelectric effect

A comparison of the theoretical predictions of Maxwell's wave theory of light summarized in Sec. 1.2.2 with the experimental findings described in Sec. 1.2.3 clearly shows that the photoelectric effect is not described by Maxwell's wave theory of light. A correct explanation of the photoelectric effect was proposed in 1905 by Albert Einstein, for which he received the 1921 Nobel Prize in Physics.

Einstein postulated that a beam of light consists of a stream of small energy *packets* (quanta), now called photons. The energy E of each photon is directly proportional to the photon's frequency f with the proportionality constant h. From the relation between frequency and wavelength $\lambda = c/f$ it follows that

$$E = hf = \frac{hc}{\lambda}. \tag{1.3}$$

The proportionality constant h is called the Planck constant, and within the currently valid definition of the SI system its value is fixed by definition and is[3]

$$h = 6.626\,070\,15 \cdot 10^{-34}\,\mathrm{J\,s} = 4.135\,667\,696 \cdot 10^{-15}\,\mathrm{eV\,s} \qquad \text{(exact)}.$$

According to Einstein's theory, if a photon incident on the photocathode is absorbed by an electron, it transfers all its energy to it. If this energy is greater than the work function A of the photocathode material—$hf > A$—the electron can be emitted from the photocathode. It follows that the photoelectric effect can occur only if $f > A/h = f_0$, where f_0 is the so-called threshold frequency. Einstein's theory is consistent with the observation that a higher light intensity with frequency above the threshold leads to a larger photocurrent: a higher intensity of light of a given frequency means a larger number of photons absorbed by the photocathode surface per unit time. Consequently, more electrons are emitted per unit time, resulting in a larger photocurrent.

According to this theory there is no need for any delay between illuminating the photocathode and electron emission. If the photon has a sufficiently high frequency (and thus energy), its absorption can immediately result in electron emission.

Finally, Einstein's theory explains why the stopping voltage for a given material is a function only of the light frequency. Since the work function is the minimum energy an electron needs to leave the photocathode (an electron may lose part of its energy in collisions inside the material before emission), we can write for the maximum kinetic energy of the photoelectrons, by energy conservation together with (1.1),

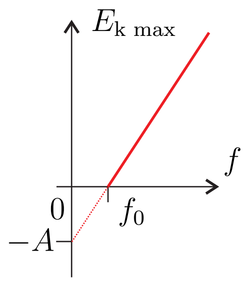

Figure 1.3:

$$E_{\mathrm{k\ max}} = hf - A \quad \Rightarrow \quad eU_{\mathrm{s}} = hf - A \quad \Rightarrow \quad U_{\mathrm{s}} = \frac{h}{e}f - \frac{A}{e}. \tag{1.4}$$

The relation (1.4) explains, in agreement with observations, why the stopping voltage increases with the light frequency and shows that it does not depend on its intensity. The dependence of the maximum kinetic energy of the photoelectrons on frequency is shown in Fig. 1.3.

[3] It is sometimes convenient to express the Planck constant in electronvolt-seconds (eV s). One electronvolt corresponds to the kinetic energy gained by an electron accelerated through a potential difference of one volt in vacuum, i.e. $1\,\mathrm{eV} = 1.602\,176\,634 \cdot 10^{-19}\,\mathrm{J}$ (exactly).

Element	Symbol	A [eV]	f_0 [PHz]	λ_0 [nm]
caesium	Cs	1,93	0,467	642
rubidium	Rb	2,13	0,515	582
potassium	K	2,24	0,542	553
sodium	Na	2,28	0,551	544
lithium	Li	2,36	0,571	525
barium	Ba	2,52	0,609	492

Table 1.1: Work functions, threshold frequencies and wavelengths for various materials.

1.3 Experiment

1.3.1 Experimental setup

The experimental setup for investigating the external photoelectric effect is shown in Fig. 1.4(a). The main components are a phototube with a caesium photocathode placed in a protective housing, whose entrance aperture is illuminated by LED modules with wavelengths 472 nm, 505 nm, 525 nm, 588 nm and 611 nm. The LED light intensity can be adjusted with a potentiometer in the range 0–100 % of the maximum value. The voltage between the cathode and the anode of the phototube can be set coarsely and finely using a pair of potentiometers.

The built-in voltmeter displays the potential difference U_{CA} in volts. The voltmeter has its positive input connected to the photocathode and its negative input to the anode of the phototube. **This means that when the photoelectrons are retarded by the external electric field (the anode is at a lower potential than the photocathode), the voltmeter indicates a positive voltage.**

A nanoammeter is integrated in the instrument to measure the photocurrent in nanoamperes. **It is connected in the circuit such that in the normal regime, when photoelectrons move through the phototube from the cathode to the anode, it displays a negative current.**

As follows from Fig. 1.2 and from the physics of the photoelectric effect, if the phototube anode is set more negative than corresponds to the stopping voltage, no photocurrent should flow through the external circuit (all photoelectrons are stopped). Nevertheless, for this particular apparatus the current reverses: this is caused by the fact that the LED light also illuminates the anode of the phototube, which then becomes a source of photoelectrons that are attracted by the external electric field towards the cathode, and a current flows in the external circuit which the nanoammeter indicates as positive.

Changing the light wavelength is done by replacing the LED module attached to the entrance of the phototube housing, see panels (b)–(d) in Fig. 1.4. The LED modules are very fragile; replace them carefully. The phototube should not be exposed to ambient light, so whenever no LED module is mounted at the entrance, put on the protective cover, see Fig. 1.4(e).

1.3.2 Processing of measured data

Verification of Einstein's formula for the maximum kinetic energy of photoelectrons (1.4) can be performed by calculating the slope of the dependence $E_{\mathrm{k\ max}}(f)$ obtained from the measured values; it should be equal to the Planck constant.

For the individual LED wavelengths λ_i you will determine by measurement the corresponding stopping voltages $U_{\mathrm{s}i}$. The maximum kinetic energies of the photoelectrons expressed in electron-volts are numerically equal to the corresponding stopping voltages expressed in volts. Calculate

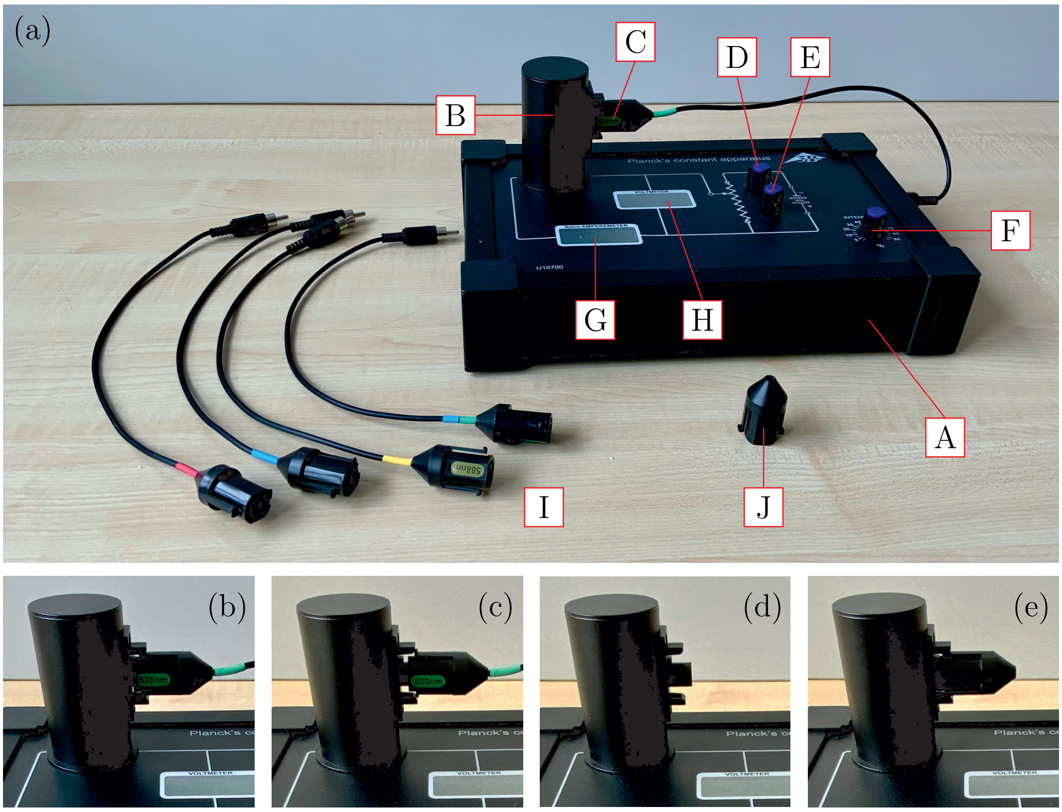

Figure 1.4: Apparatus for investigating the external photoelectric effect. Panel (a): A–main unit, B–phototube in a protective housing, C–LED module of a given wavelength, D–coarse-setting potentiometer for the phototube voltage, E–fine-setting potentiometer for the phototube voltage, F–potentiometer for setting the light intensity, G–nanoammeter display for measuring the photocurrent, H–voltmeter display for measuring the phototube voltage, I–LED modules emitting at different wavelengths, J–cover of the phototube entrance. Panel (b)–LED correctly mounted on the phototube, panel (c)–LED incorrectly mounted on the phototube, panel (d)–phototube entrance with no LED/entrance cover attached, panel (e)–entrance cover correctly mounted on the phototube.

the light frequencies for the individual LEDs as $f_i = c/\lambda_i$, where c is the speed of light in vacuum. Fit the pairs $[f_i, E_{\mathrm{kmax}i}]$ by the method of least squares[4] with a polynomial of the first degree

$$E_{\mathrm{k\ max}} = a_1 f + a_0. \tag{1.5}$$

By comparison it is seen that the slope of the linear dependence (1.5) corresponds to the Planck constant in (1.4). If you express the energy in electronvolts and the frequency in petahertz[5], you obtain the *measured* Planck constant in joule-seconds as

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

From the comparison it further follows that the intercept in (1.5) corresponds to the work function: $A = -a_0$.

[4]For this purpose you may use the least-squares implementation in the script *Universal tool for plotting graphs*, available at *https://planck.fel.cvut.cz/praktikum/*.

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

1.3.3 Measurement procedure

We ask students (and instructors) to handle the setup carefully and not to leave the entrance aperture of the phototube housing uncovered for long periods.

The following three experiments can be performed in a single measurement run.

Maximum kinetic energy of photoelectrons as a function of frequency

1. Set the potentiometer for the LED light intensity (Fig. 1.4(a) F) to 100 %.
2. Carefully mount the LED module of the given wavelength onto the entrance aperture of the phototube housing (proceed from the shortest to the longest wavelength). Connect the module to the corresponding connector on the main unit of the setup.
3. Using the coarse and fine voltage controls (Fig. 1.4(a) D, E) set the stopping voltage U_s (displayed as a positive value on the voltmeter) so that the nanoammeter display shows zero photocurrent. Record the LED wavelength and the corresponding stopping voltage.
4. Repeat steps 2–3 for all the remaining LED wavelengths.
5. Plot $E_{k\,max}(f)$, fitting the measured values by the first-degree polynomial, see Sec. 1.3.2. Compare the slope of the theoretical dependence with the Planck constant. Compute the photocathode work function and the threshold frequency.

Independence of the maximum kinetic energy of photoelectrons on the light intensity

Perform the measurement for wavelengths 472 nm, 525 nm and 611 nm.

1. Carefully mount the LED module of the given wavelength onto the entrance aperture of the phototube housing and connect the module to the corresponding connector on the main unit of the setup.
2. Set the potentiometer for the LED light intensity to 100 %.
3. Using the coarse and fine controls set the stopping voltage U_s so that the nanoammeter display shows zero photocurrent. Record the stopping voltage.
4. Repeat step 3 for the light intensity set to 80 %, 60 %, 40 % and 20 %.
5. Repeat steps 1–4 for the other two LED wavelengths.
6. Arrange the measured values in a table. Calculate, for each wavelength, by how many percent the maximum kinetic energy of the photoelectrons changes when the intensity of the incident light is changed from 20 % to 100 %.

According to theory, the maximum kinetic energy of the photoelectrons should not depend on the light intensity at all. In measurements with this apparatus you will, however, observe a slight change of $E_{k\,max}$ when the light intensity is varied. Can you suggest a reason (other than that Einstein's theory is wrong) why you measured this dependence?

Dependence of the photocurrent on the potential difference between the phototube electrodes

Perform the measurement for wavelengths 472 nm, 505 nm and 525 nm.

1. Carefully mount the LED module of the given wavelength onto the entrance aperture of the phototube housing and connect the module to the corresponding connector on the main unit of the setup.

2. Using the coarse and fine controls set the voltage between the phototube electrodes to zero.

3. Using the potentiometer for the LED light intensity, adjust the photocurrent as precisely as possible to its maximum value still displayed by the nanoammeter (-1.999 nA).

4. Measure the dependence of the photocurrent on the potential difference, $I_{\mathrm{p}}(U_{\mathrm{CA}})$, from zero up to the stopping voltage (where the photocurrent falls to zero). Record the photocurrent values as positive.

5. Repeat steps 1–4 for the other two wavelengths.

6. Plot all three dependencies $I_{\mathrm{p}}(U_{\mathrm{CA}})$ in one graph (you may fit the measured values by a low-order polynomial, e.g. third degree).

By measuring you will find that with a gradual increase of the potential difference between the phototube electrodes the photocurrent decreases gradually (not abruptly). What is the cause of this phenomenon?

1.4 References

1. H. D. Young, R. A. Freedman, A. L. Ford: *University Physics with Modern Physics*, Addison-Wesley, San Francisco, 2011.

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