Planck's "quantum of action" and external photoelectric effect **(Item No.: P2510510)**

Curricular Relevance

Area of Expertise:	**Education Level:**	**Topic:**	**Subtopic:**	**Experiment:**
Physics	University	Modern Physics	Quantum Physics	Planck's 'quantum of action' and external photoelectric effect

Difficulty	**Preparation Time**	**Execution Time**	**Recommended Group Size**
Difficult	1 Hour	2 Hours	2 Students

Additional Requirements:

Experiment Variations:

Keywords:

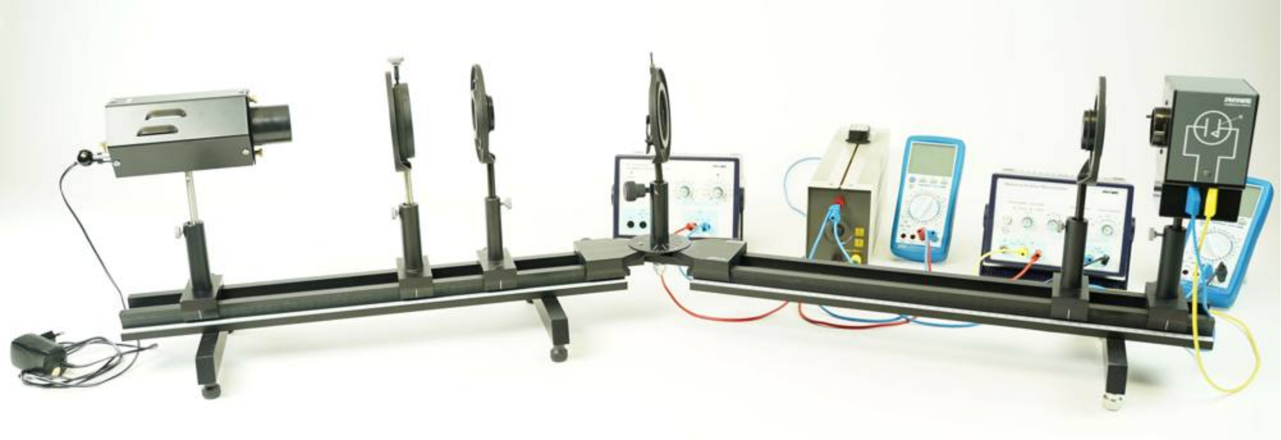
Photon energy, photon absorption, external photo effect, work function, photocell, quantum theory, Planck’s constant, grating spectrometer

Overview

Short description

Principle

The photoelectric effect is one key experiment in the development of modern physics. White light from a filament lamp is filtered by a grating spectrometer and illuminates a photocell. The maximum energy of the ejected electrons depends only on the frequency of the incident light, and is independent of its inten-sity. This law appears to be in contradiction with the electromagnetic wave theory of the light, but it be comes understandable in the frame of the corpuscular theory of light. The stopping voltage U_0 at different light frequencies is determined by the I/U characteristics of the photocell and plotted over the corres ponding light frequency f . Planck’s quantum of action is then determined from this graph.



Equipment

Position No.	Material	Order No.	Quantity
1	Photocell for h-determination, with housing	06779-00	1
2	Diffraction grating, 600 lines/mm	08546-00	1
3	Colour filter, light red, >600 nm, 93% @ 595 nm	08416-00	1
4	Slit, adjustable	08049-00	1
5	Lens holder, beam height 120 mm	08012-01	2
6	Lens, mounted, f +100 mm	08021-01	2
7	Connecting cord, 32 A, 500 mm, red	07361-01	2
8	Connecting cord, 32 A, 500 mm, blue	07361-04	2
9	Connecting cord, 32 A, 1500 mm, red	07364-01	2
10	Connecting cord, 32 A, 1500 mm, blue	07364-04	2
11	Connecting cord, 32 A, 1500 mm, yellow	07364-02	1
12	Rheostat, 100 Ohm, 1.8 A	06114-02	1
13	PHYWE power supply, 230 V, DC: 0...12 V, 2 A / AC: 6 V, 12 V, 5 A	13506-93	1
14	PHYWE Universal measuring amplifier	13626-93	1
15	Digital multimeter with NiCr-Ni thermo couple	07122-00	2
16	Optical bench expert l = 600 mm	08283-00	2
17	Base for optical bench expert, adjustable	08284-00	3
18	Turning knuckle for optical bench expert	08285-01	1
19	Slide mount for optical bench expert, h = 80 mm	08286-02	5
20	Diaphragm holder, for beam height 120 mm	08040-01	1
21	Rod D10x66 / M6x8	331876	2
22	Experimental lamp LED HEX 1	08130-99	1

Tasks

1. Calculate the light frequency f in dependence on the spectrometer angle
2. Experimentally determine the stopping voltage U_0 for different light frequencies and plot it over light frequency f .
3. Calculate Planck’s constant from the dependence of the stopping voltage U_0 on the light frequency f .

Set-up and Procedure

The experiment for the demonstration of the photoelectric effect is formed by: a photoelectric cell, the cathode of which is irradiated with a light beam characterized by the frequency f ; a potentiometer allowing to apply on the cell anode a voltage U (positive or negative with respect to the cathode); a voltmeter to measure this voltage; a microamperemeter to measure the photoelectric current I .

- Set up the two optical benches with turning knuckle such that the arrangement stands firmly on the table and the right bench can be turned
- Position the lamp at 9.0 cm, the slit at 34.0 cm and the first 100 mm-lens at 44.0 cm from the left end of the left optical bench and turn on the lamp
- Set the slit width to about the same as photocell entrance slit width
- move the lamp holder inside the lamp housing to focus the light coming out of the lamp on the plane of the slit
- Move the lens such that the light is parallel after the lens – you can assess the beam at the next wall
- Insert the 600 lines per mm grating into the diaphragm holder in the centre of the turning knuckle
- Align the grating lines vertical by observing the spectra on surrounding surfaces – same height to both sides of the grating
- Put the photocell to the right end of the right optical bench, use the slit entrance of the housing
- Focus the illuminating slit into the slit entrance of the photocell with the other 100 mm lens inserted in front of the photocell
- Record the angle as zero-angle, where all the undiffracted light enters the photocell entrance slit
- Do the electrical connections as in Fig. 2
- Set the measuring amplifier to low drift mode, amplification 10^5 and time constant 0.3 s
- Check zeroing of universal amplifier – with no connection on the input set the amplifier output voltage to zero with the zeroing button
- Set the power supply voltage on the potentiometer to 3 V, current to 1 A.
- Observe the amplifier output which is proportional to photo current in dependence on photocell bias voltage
- Measure the bias voltage for zero current for different angles in the first order diffraction spectrum of the lamp – for the 600 l /mm grating 13° to 25°.
- As soon as the light can pass the red filter (ca. above 21 ° diffraction angle), use the filter to prevent second order UV light to disturb the measurement.

Remarks on operation:

The measuring amplifier input has a resistance of 10,000 Ohm. If the amplifier is set to amplification 104, then one volt at the amplifier output corresponds to 0.0001 V at the input and thus to a current of 10 nA.
The time constant is set to avoid errors due to mains hum influence. The vernier scale at the turning knuckle can be read as follows: Take the next lower angle reading on the scale on the inside near the zero mark of the scale on the outside and add the angle reading of the vernier, where the lines of the vernier (outside, moving) and the lines of the scale on the round plate (fixed, at centre) coincide, see ex-ample on Fig. 3.

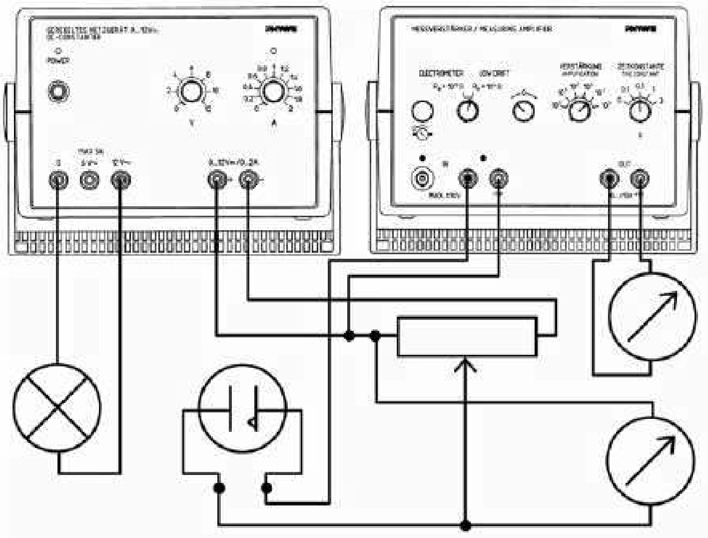


Fig. 2: Circuit diagram for the experiment.

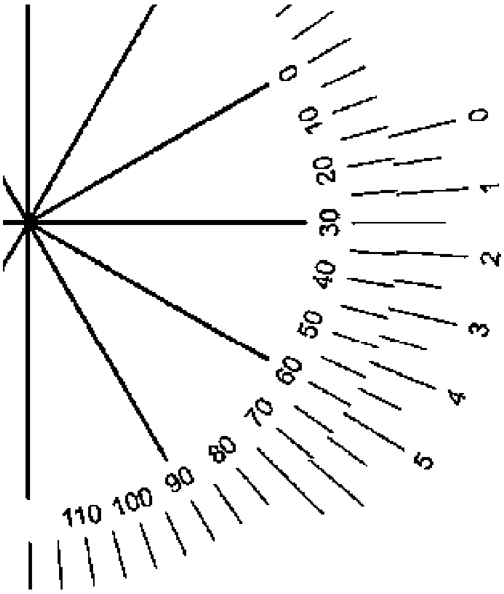


Fig. 3: Example for reading the vernier scale: The next lowest mark near the zero mark is 15°, the next marks coinciding are at 1.5°, so the angle reads 16.5°.

Theory and evaluation

The external photoelectric effect was first described in 1886 by Heinrich Hertz. It soon became clear that this effect shows certain characteristics that cannot be explained by the classical wave theory of light. For example, when the intensity of the light shining on a metal becomes more intense, the classical wave theory would expect that the electrons liberated from the metal would absorb more energy. However, experiments showed that the maximum possible energy of the ejected electrons depends only on the frequency of the incident light and is independent of its intensity.
The theoretical explanation was given by Einstein in 1905. He suggested that light could be considered to behave like particles in some respect, moving with a constant velocity (the speed of light in vacuum) and possessing the energy $E = hf$. Einstein's explanation of the photoelectric effect, demonstrating the particle-like light behavior of photons, contributed to the development of quantum theory. Thus, the external photoelectric effect is one of the key experiments in the development of modern physics and Einstein obtained the Nobel Prize in Physics “for his discovery of the law of the photoelectric effect“.

Task 1: Calculate the light frequency f in dependence on the spectrometer angle

The frequency of the light irradiating the photocell is determined using the following equation:

$d \cdot \sin\alpha = n \cdot \lambda$ (1)

$\alpha = \arcsin(\lambda/d)$ (2)

α is the spectrometer angle, d is the constant of the grating (here: 1/600 mm), λ is the wavelength of the emitted light and the order of diffraction n is 1 in this case.
The light frequency f can be calculated from the wavelength λ by $f = c/\lambda$ with speed of light $c = 299792458 m/s$.

Task 2: Determine the stopping voltage U_0 experimentally for different light frequencies and plot it over the light frequency f .
Inside the photo-cell, a cathode with special low-work function coating is situated together with a metal anode in a vacuum tube. If a photon of frequency f strikes the cathode, then an electron can be liberated from the cathode material (external photoelectric effect) if the photon energy is sufficient.
If the emitted electrons reach the anode, they are absorbed by it due to the anode work function and the result is a photo current.
The photoelectric effect is an interaction of a photon with an electron. In this reaction momentum and energy are conserved, the electron absorbs the photon and has after the reaction the full photon energy hf . If the energy of the photon hf is greater than the extraction work W_c (cathode work function), the electron can after the reaction leave the substance with a maximum kinetic energy $W_{kin} = hf - W_C$. This is called external photoelectric effect and described by:

$hf = W_C + W_{kin}$ (Einstein's equation) (3)

The kinetic energy W_{kin} for the emitted electrons is determined using the stopping electric field method: A negative bias with respect to the cathode is applied on the photoelectric cell anode. This decelerates the electrons and thus decreases the photoelectric current intensity I since not all electrons have maximum energy but they have an energy distribution. The value of the bias where no electron reaches the anode and I becomes zero is called stopping voltage and is quoted U_0 .
Plotting I over the applied bias voltage U_{bias} reveals the dependence of U_0 on the wavelength λ of the incident light.

Task 3: Calculate Planck’s constant from the dependence of the stopping voltage on the light frequency.
Electrons can only reach the anode if their kinetic energy W_{kin} is greater than the energy they lose flying against the direction of the electric field created by the bias voltage U_{bias} plus the unknown electric field due to the contact voltage U_{AC} between the anode and cathode, which has the same direction as the bias voltage, see Fig 3.
As the contact voltage is in the same order of magnitude as the bias voltage, we cannot neglect it. Therefore, it is not possible to determine the absolute kinetic energy of the electrons. Nevertheless, the Planck’s constant can be calculated from the dependence of the stopping voltage on the light frequency, as the following considerations show:
At the stopping voltage U_0 , the kinetic energy W_{kin} of the electron equals the energy lost in the electric field eU (U including the stopping voltage U_0 and the contact voltage U_{AC}):

$e(U_0 + U_{AC}) = W_{kin}$ (4)

The contact voltage is calculated from the electrochemical potentials of anode U_A and cathode U_C . Multiplication of both with electron charge $e = 1.602 \cdot 10^{-19}$ As gives their corresponding work functions W_A and W_C . So equation (4) is equivalent to

$e(U_0 + U_{AC}) = W_{kin}$ (5)

To calculate Planck’s constant h using the photoelectric effect, we compare (5) with Einstein equation (3):

$W_{kin} = eU_0 + W_A - W_C = hf - W_C$ (6)

Accordingly, the cathode work function does not appear in the formula for the stopping voltage and (6) can be written as the following linear function

$$eU_0 = hf - W_A$$

or

$$U_0 = f \cdot hle - U_A \quad (7)$$

As U_A is a constant, a linear relationship exists between the stopping voltage U_0 and the light frequency f . The slope of the linear function gives Planck's constant h .
The measured slope is:

0.00329 V/THz

Multiplication with e gives: $h = 5.27 \cdot 10^{-34} Js$
The calculated value may deviate ± 25 % from the **literature value**: $h = 6.62 \cdot 10^{-34} Js$.

Table 1: Results

spectometer angle	λ/nm	$f/10^{12} Hz$	U_0/V
13,5	389	772	1,3
14	403	744	1,2
15	431	696	1,05
16,5	473	634	0,9
18	515	582	0,7
19	543	552	0,55
20	570	526	0,47
22	624	480	0,32
24	678	442	0,25

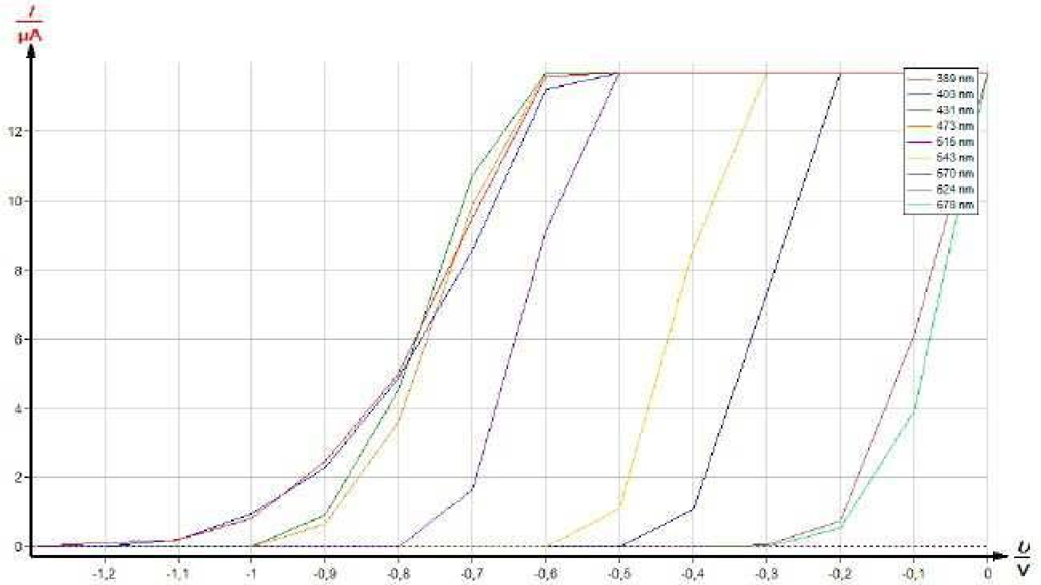


Fig. 4: The photoelectric current intensity I as a function of the bias voltage at different frequencies of the irradiated light.

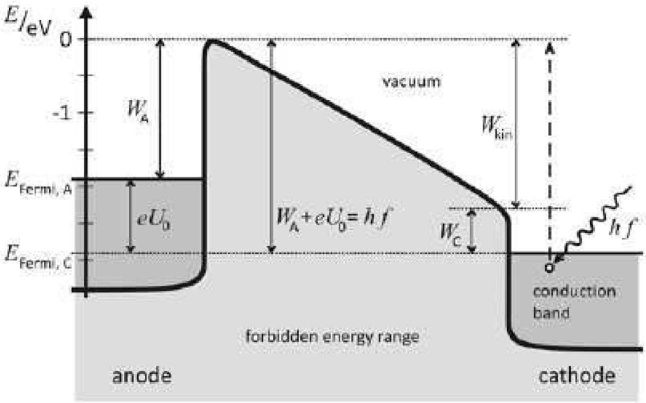
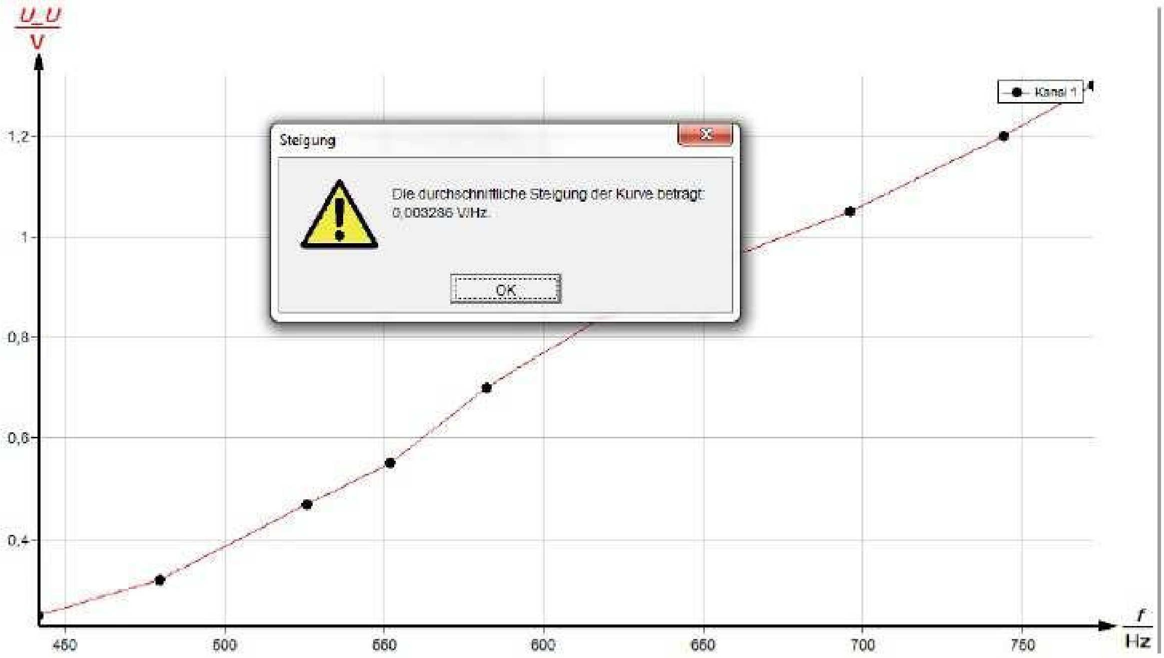


Fig. 5: Energy diagram for electrons in a photocell illuminated with \lambda =436\mathit/f=688\mathit and bias $U_0 = 1V$.

Notes

The cathode work function does not appear in the formula for the stopping voltage. This is due to the fact that the electrons come from Fermi-level in the cathode and then have to reach the anode surface and thus already have been able to pass the cathode surface.
The cathode work function on the other hand determines whether the photon energy is sufficient to liberate an electron from the cathode. Historically, this photoeffect threshold wavelength was also important for the discovery of this effect and only later was understood when the electron energy spectrum of the liberated electrons was systematically examined in dependence on light frequency and intensity.
Determining the stopping voltage U_0 you will find curves having only a small slope when crossing the x axis (zero point). An exact determination of the stopping voltage is therefore complicated.
There is a negative current for higher bias voltages. This current is due to the photo current from anode to cathode. Also from the anode electrons can be liberated. The number of electrons there also depends on light frequency and in a different way than for the cathode. It can be assumed, that the intensity and wavelength sensitivity of the reverse photo electron current anode to cathode is different from the one of the larger cathode to anode electron current. So the zero point shift per light intensity due to this effect is different for different wavelengths making the zero point of the U/I characteristic curve of the photocell a not very reliable measure.
The overall reverse current can nevertheless be regarded as small because of the far lower work function of the cathode compared to the anode. This justifies to neglect this effect.
Else the zero point shift in dependence on intensity would have to be measured for each wavelength and would have to be taken into account trying to achieve a normalization with respect to intensity.
Since effects of the electron energy distribution are also present, the gain in precision by this procedure will not be so great as to generally recommend it. Both the work function for the electrons to leave the substance and the electron energy before the reaction with the photon have no sharp extrema so that the overall achievable precision of this method is limited.
For a precise measurement of Planck's constant X-ray measurements are more suitable, but the photoelectric effect experiment has its justification by its great historic relevance.



Die durchschnittliche Steigung der Kurve beträgt:
0,003236 V/Hz.

Fig. 6: Stopping voltage U_0 as a function of the frequency of the irradiated light.