Planck's "quantum of action" and external photoelectric effect

Physics | Modern Physics | Quantum physics

Difficulty level	Group size	Preparation time	Execution time
-	-	-	-

This content can also be found online at:

https://www.curriculab.de/c/698eea107f3590000271dc27

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General information

Description

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Photomultipliers

Practical applications of photoelectric effects include:

- Photomultipliers: they significantly amplify the current produced by incident light to measure low light intensity. They are used in imaging technologies, low-light spectroscopy, medical devices and optical imaging.

  \Photocells: Exposing light to photocells causes the emission of electrons, which in turn causes a current. They can be found in luxmeters, cameras and camcorders

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Other teacher information (1/2)

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Prior knowledge

Each particle of light, called a photon, has a characteristic energy proportional to the frequency of light. When a photon hits an electron on a surface, the electron is emitted if it acquires more energy than the work of escape. If the energy of the photon is too low, the electron cannot be ejected. The emitted electrons are called photoelectrons.

Principle

The photoelectric effect is one of the key experiments in the development of modern physics. filtered by the diffraction grating of the spectrometer and illuminates the photocell. The maximum energy of the emitted electrons depends only on the frequency of the incident light and does not depend on its intensity. This law seems to contradict the electromagnetic wave theory of light, but becomes understandable within the framework of the corpuscular theory of light. Locking voltage U_0 at different light frequencies is determined by I/U volt-ampere characteristics of the photocell and is plotted at the appropriate light frequency f. The Planck action quantum is then determined from this graph.

Other teacher information (2/2)

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Learning Objective

Students should investigate the properties of the photoelectric effect as a function of the frequency of light.

Tasks

1. Calculate the frequency of light f depending on the angle of the spectrometer.
2. Determine the locking voltage experimentally U_0 for different frequencies of light and plot it on a graph of frequency dependence f
3. Calculate Planck's constant from the dependence of the locking voltage U_0 of the light frequency f

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Safety instructions

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For this experiment, the general guidelines for safe experimentation in science teaching apply.

Do not use voltages outside the operating voltage range.

Theory (1/7)

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The external photoelectric effect was first described in 1886 by Heinrich Hertz. It soon became clear that this effect exhibited certain characteristics that could not be explained by the classical wave theory of light. For example, when the intensity of light incident on a metal is greatly increased, classical wave theory expects electrons emitted from the metal to absorb more energy. However, experiments have shown that the maximum possible energy of the emitted electrons depends only on the frequency of the incident light and is independent of its intensity.

A theoretical explanation was given by Einstein in 1905. He suggested that under certain conditions light can behave as particles travelling at a constant speed (the speed of light in a vacuum) and possessing energy: $E = hf$. Einstein's explanation of the photoelectric effect, demonstrating the particle-like behaviour of photons of light, 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 received the Nobel Prize in Physics "for discovering the law of the photoelectric effect".

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Theory (2/7)

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Problem 1: Calculate the frequency of light f depending on the angle of the spectrometer

Frequency of light f is determined using the following equation:

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

$$\alpha = arcsin(\lambda / d) \text{(2)}$$

α - angle of the spectrometer, d - grid constant (here: 1/600 mm), λ - wavelength of the emitted light and order of diffraction n in this case is equal to 1 .

Frequency of light f can be calculated by the formula $f = c/\lambda$ where λ - wavelength, and (c = 299792458 m/s - \) the speed of light.

Theory (3/7)

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Problem 2: Determine experimentally the locking voltage U_0 for different frequencies of light and plot it as a function of light frequency f.

Inside the photovoltaic cell, together with the metal anode, a cathode with a special coating with low output work is located in a vacuum tube. If a photon with a frequency f strikes the cathode, the electron can then be released from the cathode material (external photoelectric effect) if the photon has sufficient energy. If the emitted electrons reach the anode, they are absorbed by the anode due to the work of the anode output, and the result is a photocurrent. The photoelectric effect is the interaction of a photon with an electron.

As a result of this interaction, momentum and energy are conserved, and the electron absorbs the photon and afterwards has the total energy of the photon $h \cdot f$ If the energy of a photon $h \cdot f$ is greater than the cathode output work W_c then the electron after interaction can leave the substance with maximum kinetic energy $W_{kin} = h \cdot f - W_c$.

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Theory (4/7)

This is called the external photoelectric effect and is described as:

$$h \cdot f = W_c + W_{kin} \text{ (Einstein's equation) (3)}$$

Kinetic energy W_{kin} for the emitted electrons is determined using the method of delayed electric field: a negative bias is applied to the anode of the photocell with respect to the cathode.

This slows down the electrons and thus reduces the intensity of the photovoltaic current \(I \) *, since not all electrons have the maximum energy, but they have an energy distribution. The bias value when no electron reaches the anode and the \(I \) becomes equal to zero is called the locking voltage and is denoted as* U_0*.*

D graph of current dependence I *of the applied bias voltage* U_{bias} *shows the dependence* U_0 *wavelength* λ *of incident light.*

Theory (5/7)

Problem 3: Calculate Planck's constant from the dependence of the gating voltage on the frequency of light.

Electrons can reach the anode only if their kinetic energy W_{kin} is greater than the energy they lose by counteracting the electric field set by the bias voltage U_{bias} and unknown electric field due to potential difference U_{AC} between anode and cathode, which has the same direction as the bias voltage.

Since the potential difference is of the same order of magnitude as the bias voltage, we cannot neglect it. Consequently, it is impossible to determine the absolute kinetic energy of electrons. Nevertheless, Planck's constant can be calculated from the dependence of the locking voltage on the frequency of light by the following considerations:

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Theory (6/7)

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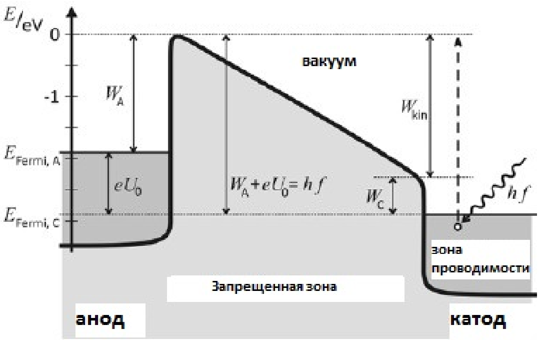
At locking voltage U_0 kinetic energy W_{kin} of the electron is equal to the energy lost in the electric field eU (U = locking voltage U_0 and potential difference U_{AC}):

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

The potential difference (contact voltage) is calculated from the electrochemical potentials of the anode. U_A and cathode U_C . Multiplying them both by the electron charge $e = 1.602 \cdot 10^{-19}$Клwe obtain the corresponding output work W_A и W_C. Equation (4) is equivalent to

$$eU_0 + W_A - W_C = W_{kin} \quad (5)$$



Circuit diagram for the experiment

Theory (7/7)

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To calculate Planck's constant $h$using the photoelectric effect, let us compare formula (5) with Einstein's equation (3):

$$W_{kin} = eU_0 + W_A - W_C = h \cdot f - W_C \quad (6)$$

The cathode output work does not appear in the formula for the gating voltage, and equation (6) can be written as the following linear function

$$eU_0 = h \cdot f - W_A \text{ or}$$

$$U_0 = \frac{h}{e} f - U_A \quad (7)$$

Since U_A is a constant, then there is a linear relationship between the locking voltage U_0 and the frequency of light f. The slope of the linear function gives Planck's constant h .

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Equipment

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Position	Material	Item No.	Quantity
1	Photocell for h-determination	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	08049-01	1
5	Component holder	08043-00	2
6	Lens made of glass, biconvex, f = + 100 mm	08051-00	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, 160 W	06114-03	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	Ring for component holder	08044-00	2
16	PHYWE Digital multimeter, 600V AC/DC, 10A AC/DC, 20 MΩ, 200 µF, 20 kHz, −20°C...760°C	07122-00	2
17	Post, L 100 mm, D 12 mm	08750-06	1
18	Optical bench expert l = 600 mm	08283-00	2
19	Setscrew for optics, Set of 10 pcs	08750-15	1
20	Base for optical bench expert, adjustable	08284-00	3
21	Turning knuckle for optical bench expert	08285-01	1
22	Slide mount for optical bench expert, h = 80 mm	08286-02	5
23	Universal Holder, rotational	08040-02	1
24	Experimental lamp LED HEX 1	08130-99	1

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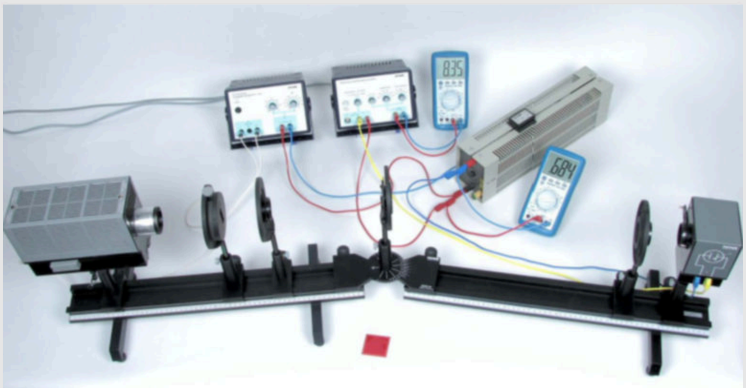
Student information

Setup



Experimental setup

The experimental setup for demonstrating the photoelectric effect consists of:

- A photocell whose cathode is irradiated by a light beam characterised by a frequency of f
- potentiometer allowing the voltage to be applied U (positive or negative with respect to the cathode),
- voltmeter to measure this voltage,
- microammeter for measuring photoelectric current I.

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Procedure (1/4)

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Position the two optical benches with the rotary adjuster so that the unit is stable on the table and the right bench can be rotated.

Position the lamp at 9.0 cm, the slit at 34.0 cm and the first lens with a focal length of $f = +100 \text{мм}$ 44.0 cm from the left edge of the left optical bench and switch on the lamp.

Set the slit width approximately equal to the entrance slit width of the photocell.

Move the lamp holder inside the lamp housing to focus the light coming out of the lamp onto the plane of the slit.

Move the lens so that the light after the lens is parallel.

Insert the 600 lines per mm grid into the aperture holder in the centre of the rotary regulator (cam).

Procedure (2/4)

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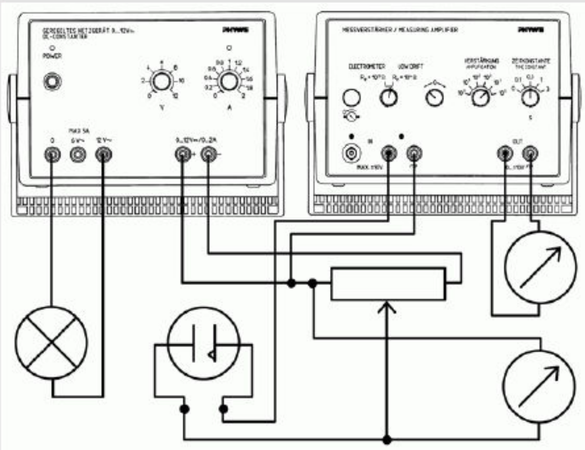
Align the grating lines vertically by observing the spectra on the surrounding surfaces - of equal height on either side of the grating.

Place the photocell at the right end of the right optical bench using the slot on the housing.

Focus the illumination slit into the entrance slit of the photocell with a second lens with focal length $f = +100 \text{мм}$ inserted in front of the photocell.

Write the angle at which all unscattered light enters the entrance slit of the photocell as zero angle.

Make the electrical connections as shown in the illustration.



Circuit diagram for the experiment

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Procedure (3/4)

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Set the measuring amplifier to low drift mode, gain 10^5 and a time constant of 0.3 seconds.

Check zeroing of the universal amplifier - if there is no connection at the input, set the amplifier output voltage to zero with zeroing control

Set the supply voltage on the potentiometer to 3 V, the current to 1 A.

Observe the output of the amplifier, which is proportional to the photocurrent as a function of the photocell bias voltage.

Measure the bias voltage for zero current for different angles in the first-order diffraction spectrum - for a 600 strokes/mm grating from 13° - 25°. As soon as the light can pass through the red filter (diffraction angle of about 21°), use a filter so that the second-order UV light does not interfere with the measurement.

Measure the offset voltage for zero current for different frequencies.

Procedure (4/4)

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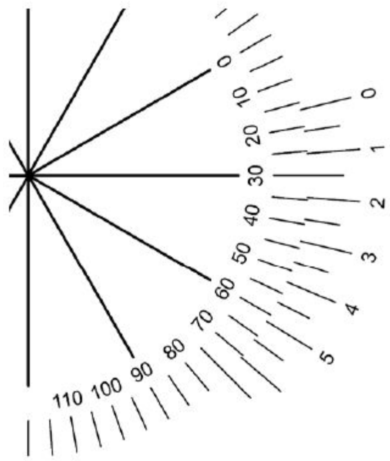
Operational Notes:

The input of the measuring amplifier has a resistance of $10000\,\Omega$. If the amplifier is set to gain 10^4 then $1\,\mathrm{V}$ at the output of the amplifier corresponds to $0.0001\,\mathrm{V}$ at the input and thus the current is equal to $10\,\mathrm{nA}$.

The time constant is set to avoid errors due to the influence of mains noise. The nonius scale on the rotary cam can be read as follows: take the next lower angle value on the scale on the inside near the zero mark of the scale on the outside and add the nonius angle value where the nonius lines (outside, movable scale) and the scale lines on the round plate (fixed, centre) coincide.



Example for reading a nonius scale

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Evaluation (1/3)

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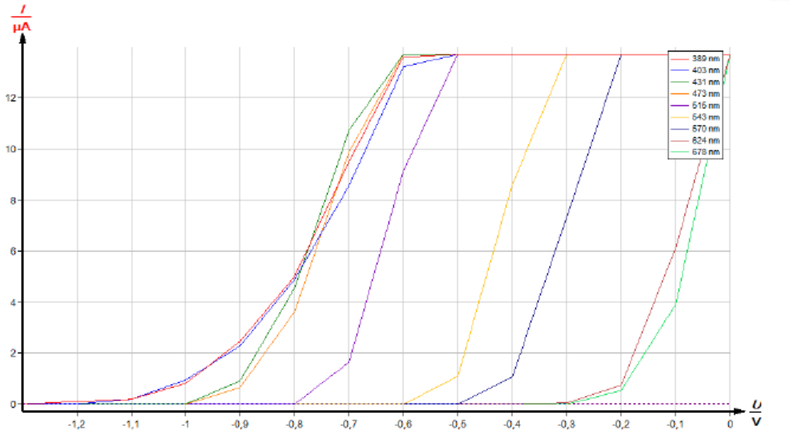
Angle	λ, nm	f, 10^{12}Hz	U_0, V
13.5	389	772	1.3
14	403	744	1.2
15	431	696	1.05
16.5	473	634	0.9
22	624	480	0.32

Spectrometer results



Photovoltaic current strength I as a function of bias voltage at different frequencies of irradiated light

Evaluation (2/3)

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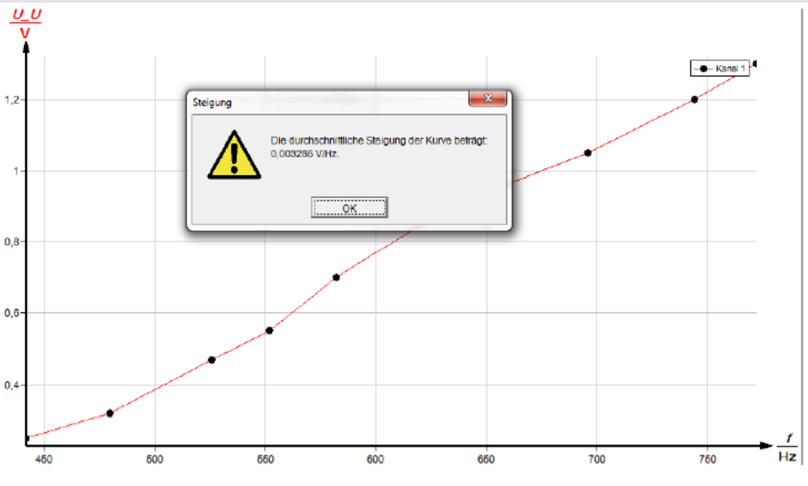
The slope of a linear function is equal to Planck's constant h:

The measured slope is:
$0,00329\ \mathrm{V/THz}$

Multiplication by *e* gives:
$h = 5.2710^{-34}\ \mathrm{Js}$

The calculated value may deviate by ± 25% from the tabulated value:

$h = 6.62.10^{-34}\ \mathrm{Js}$



Locking voltage U_0 depending on the frequency of irradiated light

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Evaluation (3/3)

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What are the causes of measurement error of *h*?

- [ ] Uncertainty of locking stresses
- [ ] Light frequency spread
- [ ] Intensity of the emitted light beam

Check it out

What quantities affect the photoelectric effect?

- [ ] The work of yielding a substance
- [ ] Frequency of incident light
- [ ] Intensity of incident light

Check it out

Slide	Evaluation / Total
Slide 22: Numerous tasks	**0/4**

Total score 0 / 4

Show solutions

Remember

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