Planck's "quantum of action" and photoelectric effect (line separation by interference filters)

Physics > Modern Physics > Quantum physics

Difficulty level	Group size	Preparation time	Execution time
hard	2	45+ minutes	45+ minutes

Robert-Bosch-Breite 10
37079 Göttingen

Tel.: 0551 604 - 0
Fax: 0551 604 - 107

info@phywe.de
www.phywe.de

General information

Application

Photomultiplier tube

Photomultiplier tubes utilize the multiplication of electrons by secondary emission to measure low light intensity. They amplify the current produced by incident light enormously, as much as 100 million times, in multiple dynode stages. They can as well detect invidual photons when the incident flux of light is low.

Photomultiplier tubes are used in imaging technology, low light level spectroscopy, medical equipments and optical imaging.

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Other information (1/2)

Prior knowledge

Each particle of light, called photon, has a characteristic energy which is proportional to the frequency of the light. When a photon hits an electron on a surface, the electron is emitted if it acquires more energy than the work function. If the photon energy is too low, the electron is unable to be ejected. The emitted electrons are called photoelectrons.

Scientific principle

The photoelectric effect is one key experiment in the development of modern physics. White light from a filament lamp is filtered by an interference filter 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 intensity. This law appears to be in contradiction with the electromagnetic wave theory of the light, but it becomes understandable in the frame of the corpuscular theory of light.

Other information (2/2)

Learning objective

To learn Planck's quantum and the dependance of photoelectric effect on light frequencies.

Tasks

1. Experimentally determine the stopping voltage U_0 for different light frequencies and intensities and plot it over light frequency *f*.
2. Calculate Planck's constant from the dependence of the stopping voltage U_0 on the light frequency *f*.

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Safety instructions

For this experiment the general instructions for safe experimentation in science lessons apply.

Do not use a voltage in excess of the operating voltage range.

Do not exert mechanical force on the vacuum cell.

Theory (1/6)

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

$$E = h \cdot f$$

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Theory (2/6)

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".

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 is sufficiently energetic.

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 $h \cdot f$.

Theory (3/6)

If the energy of the photon $h \cdot f$ 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 $W_{kin} = h \cdot f - W_c$. This is called external photoelectric effect and described by:

$$h \cdot f = W_c + W_{kin} \qquad \text{(Einstein's equation)} \quad (1)$$

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.

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Theory (4/6)

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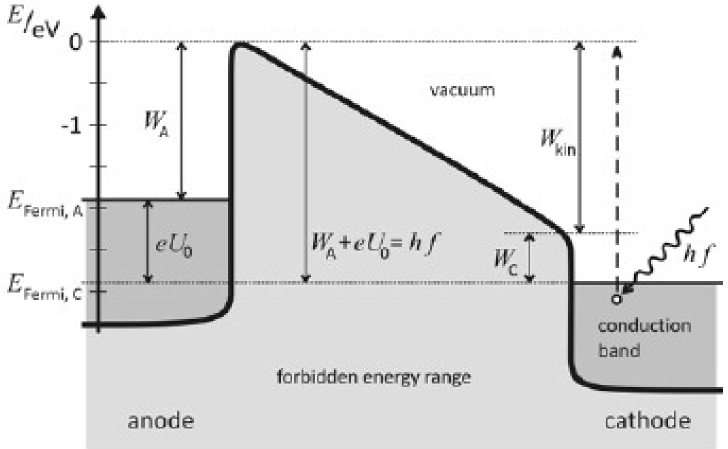

Energy diagram for electrons in a photocell illuminated with $\lambda = 436 nm / f = 688 THz$and bias $U_0 = 1 V$

Electrons can only reach the anode if their kinetic energy W_{kin} is greater than the energy they lose running counter to the electric field set up 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

Theory (5/6)

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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, due to the following considerations:

At the stopping voltage U_0, the kinetic energyW_{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}):

$$e(U_0 + U_{AC}) = W_{kin} \qquad (2)$$

The contact voltage is calculated from the electrochemical potentials of anode U_A and cathode U_C and multiplication of both with electron charge $e = 1.602 \cdot 10^{-19} As$ gives their corresponding work functions W_A and W_C. Equation (2) is equivalent to

$$eU_0 + W_A - W_C = W_{kin} \qquad (3)$$

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Theory (6/6)

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To calculate Planck's constant *h* using the photoelectric effect, we compare (2) with Einstein equation

$$W_{kin} = eU_0 + W_A - W_C = h \cdot f - W_C$$

Accordingly, the cathode work function does not appear in the formula for the stopping voltage and (3) can be written as the following linear function

$$eU_0 = h \cdot f - W_A$$

or

$$U_0 = \frac{h}{e} f - U_A \qquad (4)$$

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 light frequency *f* can be calculated from the wavelength *λ* of the interference filters by *f=c/λ* with speed of light c = 299792458 m/s.

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Equipment

Position	Material	Item No.	Quantity
1	Photocell for h-determination, with housing	06779-00	1
2	Interference filters, set of 3	08461-00	1
3	Interference filters, set of 2 (blue-violet and blue-green)	08463-00	1
4	Power supply with holder for spectral lamps E27	08121-97	1
5	Spectral lamp Hg, E27 base	08122-14	1
6	PHYWE Power supply, 230 V, DC: 0...12 V, 2 A / AC: 6 V, 12 V, 5 A	13506-93	1
7	PHYWE Universal measuring amplifier	13626-93	1
8	Digital multimeter, 600V AC/DC, 10A AC/DC, 20 MΩ, 200 µF, 20 kHz, −20°C… 760°C	07122-00	2
9	Rheostat, 100 Ohm, 1.8 A	06114-02	1
10	Connecting cord, 32 A, 500 mm, red	07361-01	4
11	Connecting cord, 32 A, 500 mm, blue	07361-04	3
12	Connecting cord, 32 A, 500 mm, yellow	07361-02	1
13	Connecting cord, 32 A, 1000 mm, blue	07363-04	1
14	Post, L 75 mm, D 12 mm	08750-05	1
15	Setscrew for optics, set of 5 pieces	08750-14	1
16	Barrel base expert	02004-00	2

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Setup and procedure

Setup

The experimental setup

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 a voltage U to the cell (positive or negative with respect to the cathode),
- a voltmeter to measure this voltage,
- a microampere meter to measure the photoelectric current.

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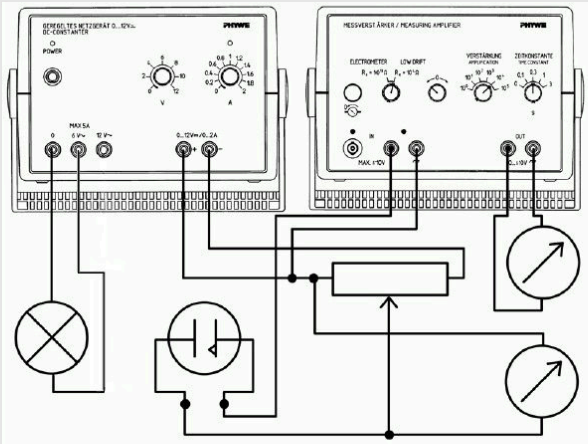
Procedure (1/2)

Do the electrical connections:

- Set the measuring amplifier to low drift mode, amplification 10^4 and time constant 0.3s
- Check zeroing of universal amplifier – with no connection on the input set the amplifier output voltage to zero with the zeroing control
- Set the power supply voltage on the potentiometer to 3V, current to 1A.
- Put the photocell directly in front of the lamp, use the round opening of the slider.



Electrical connections for the experiment

Procedure (2/2)

- The interference filters are fitted one after the other to the light entrance of the photo-cell.
- 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 frequencies.

Remarks on operation:

The measuring amplifier input has a resistance of 10,000 Ohm. If the amplifier is set to amplification 10^4, 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.

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Evaluation (1/5)

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λ/nm	U_0/V	$f/10^{12}$
366	-1.50	820
405	-1.20	741
436	-1.00	688
546	-0.50	550
578	-0.40	520

Measured bias voltages for different light frequencies

- Measure the bias voltage for zero current for different frequencies
- Plotting I over the applied bias voltage U_{bias} reveals the dependence of U_0 on the wavelength λ of the incident light and lack of dependence on light intensity. The light intensity determines the photo current strength.

Evaluation (2/5)

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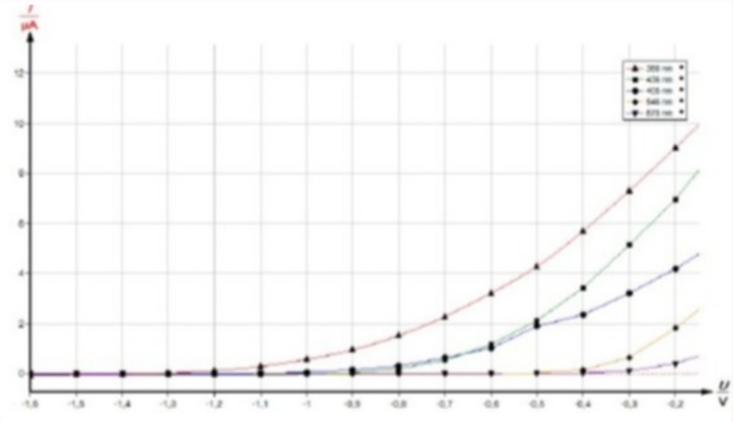
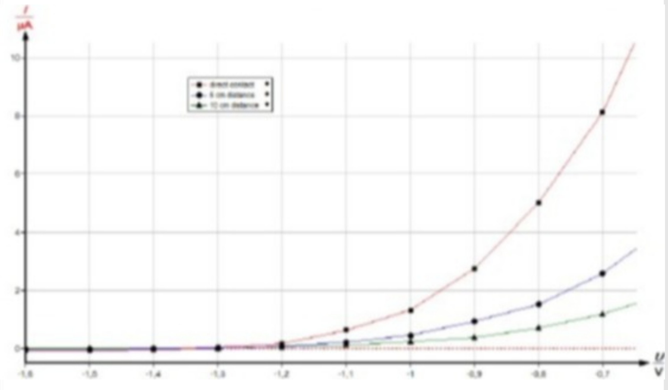


The photoelectric current intensity I as a function of the bias voltage at different frequencies of the irradiated light



The photoelectric current intensity I as a function of the bias voltage at different intensities

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Evaluation (3/5)

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Regarding equation (4):

The measured slope is: $0.00366 \frac{V}{10^{12}\,\frac{1}{s}}$

Multiplication with *e* gives:
$h = 5.59 \cdot 10^{-34} Js$

The calculated value may deviate ± 20 % from the literature value:
$h = 6.62 \cdot 10^{-34} Js$

Stopping voltage U_0 as a function of the frequency of the irradiated light

Evaluation (4/5)

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Fill in the blank:

Planck's constant is a physical constant that relates the ______ carried by a photon to its ______. Regarding to its relation, the ______ from the light with ______ wavelength have higher frequency, and hence they have ______ energy.

- photons
- lower
- higher
- frequency
- energy

Check

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Evaluation (5/5)

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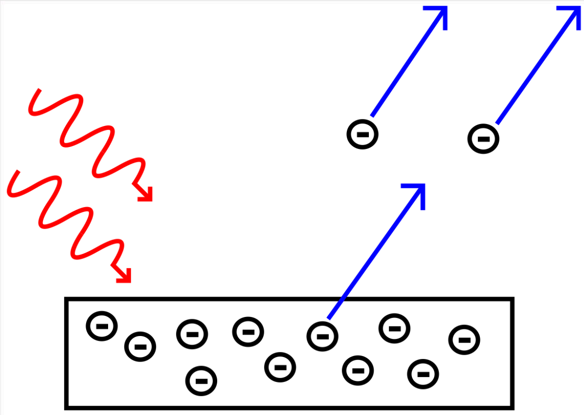
How does the intensity affect the photoelectric current?

- [ ] The photoelectric effect increases
- [ ] The number of photoelectrons ejected increases
- [ ] The number of photoelectrons ejected decreases
- [ ] Energy of electrons increases

Check



Photoelectric effect

Slide	Score / Total
Slide 20: Planck's constant	0/5
Slide 21: Photoelectric effect	0/2

Total Score 0/7

Show solutions Retry

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