External photoelectric effect and Planck's constant – wavelength selection with interference filters

TEP

Related Topics

Photon energy, photon absorption, external photo effect, work function, photocell, interference filter, quantum theory, Planck's constant

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. The stopping voltage U_0 at different light frequencies is determined by the I/U characteristics of the photocell and plotted over the corresponding light frequency f. Planck's quantum of action is then determined from this graph.

Equipment

1	Photocell with housing	06779-00
1	Interference filters, set of 3	08461-00
1	Interference filters, set of 2	08463-00
1	Experimental lamp 5	11601-00
1	Power supply 0…12 V DC / 6 V, 12 V AC	13505-93
1	Universal measuring amplifier	13626-93
2	Digital multimeter, 3 1/2 digits	07122-00
1	Variable resistor, 100 Ohm, 1,8 A	06114-02
4	Connecting cable, 4 mm plug, 32 A, red, 50 cm	07361-01
3	Connecting cable, 4 mm plug, 32 A, blue, 50 cm	07361-04
1	Connecting cable, 4 mm plug, 32 A, yellow, 50 cm	07361-02
2	Connecting cable, 4 mm plug, 32 A, black, 50 cm	07361-05
1	Connecting cable, 4 mm plug, 32 A, blue, 100 cm	07363-04
1	TESS expert CD-ROM Laboratory Experiments	16502-42

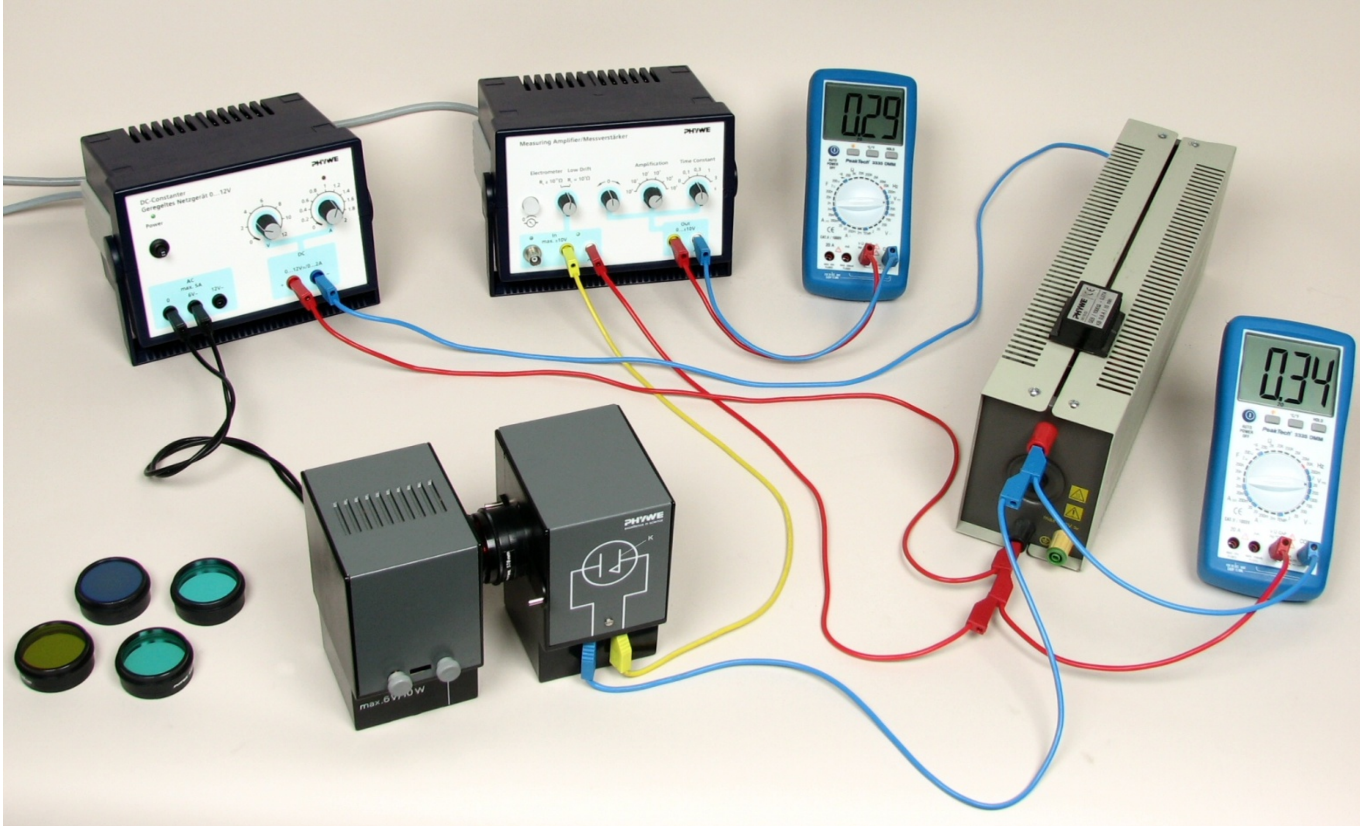


Fig. 1: Set-up of experiment P2510402

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.

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

- The experimental set-up is as shown in Fig. 1.
- Do the electrical connections as in Fig. 2
- Set the measuring amplifier to low drift mode, amplification 10^4 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 control
- Set the power supply voltage on the potentiometer to 3 V, current to 1 A.
- Put the photocell directly in front of the lamp, use the round opening of the slider
- 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.

Theory and evaluation

The external photoelectric effect was first described in 1886 by Heinrich Hertz. It soon became clear that this ef-

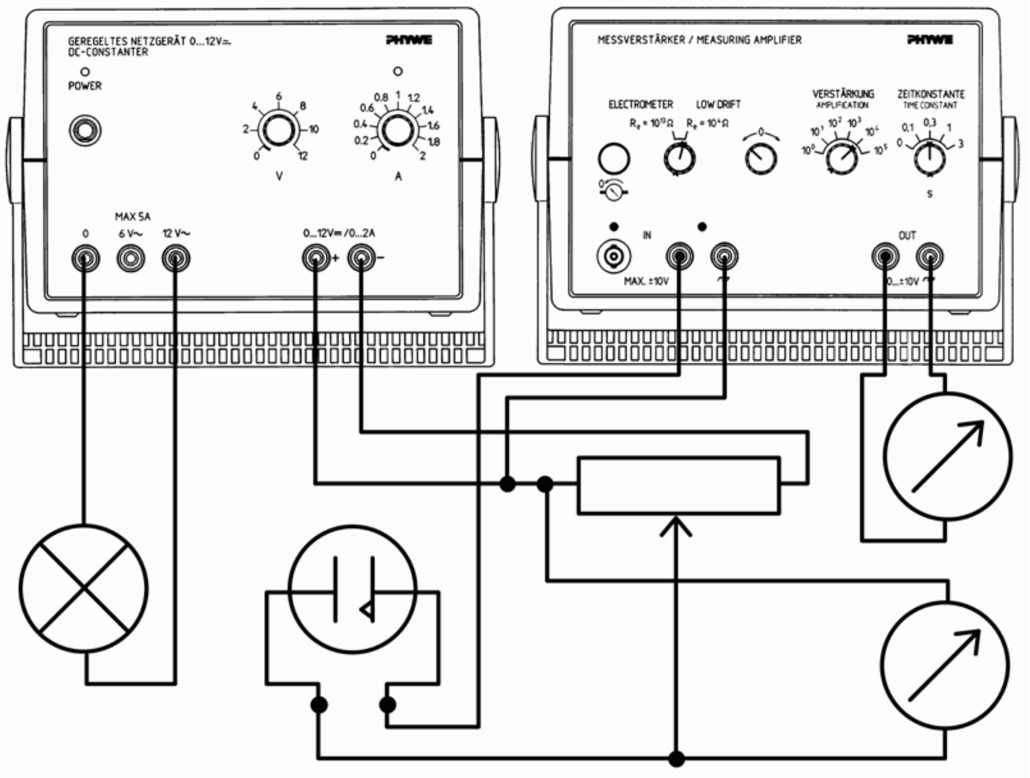


Fig. 2: Electrical connections for the experiment

fect 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: Determine the stopping voltage U_0 experimentally for different light frequencies and intensities 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 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 $h\,f$. If the energy of the photon $h\,f$ 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 $W_{kin} = h\,f - W_C$. This is called external photoelectric effect and described by:

$$h\,f \quad = W_C + W_{kin} \quad \text{(Einstein's equation)} \quad (1)$$

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.

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, see Fig. 3. The light intensity determines the photo current strength.

Table 1: Results

λ/nm	U_0/V	$f/10^{12}$ Hz
366	-1,50	820
405	-1,20	741
436	-1,00	688
546	-0,50	550
578	-0,40	520

Task 2: 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 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, see Fig 3.

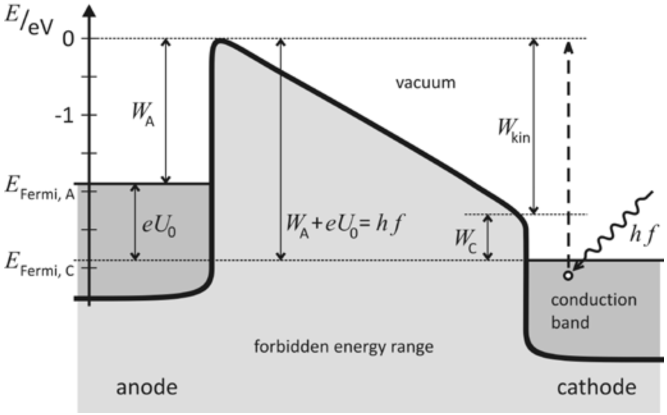


Fig. 3: Energy diagram for electrons in a photocell illuminated with λ = 436 nm/f=688 THz and bias U_0 = 1 V

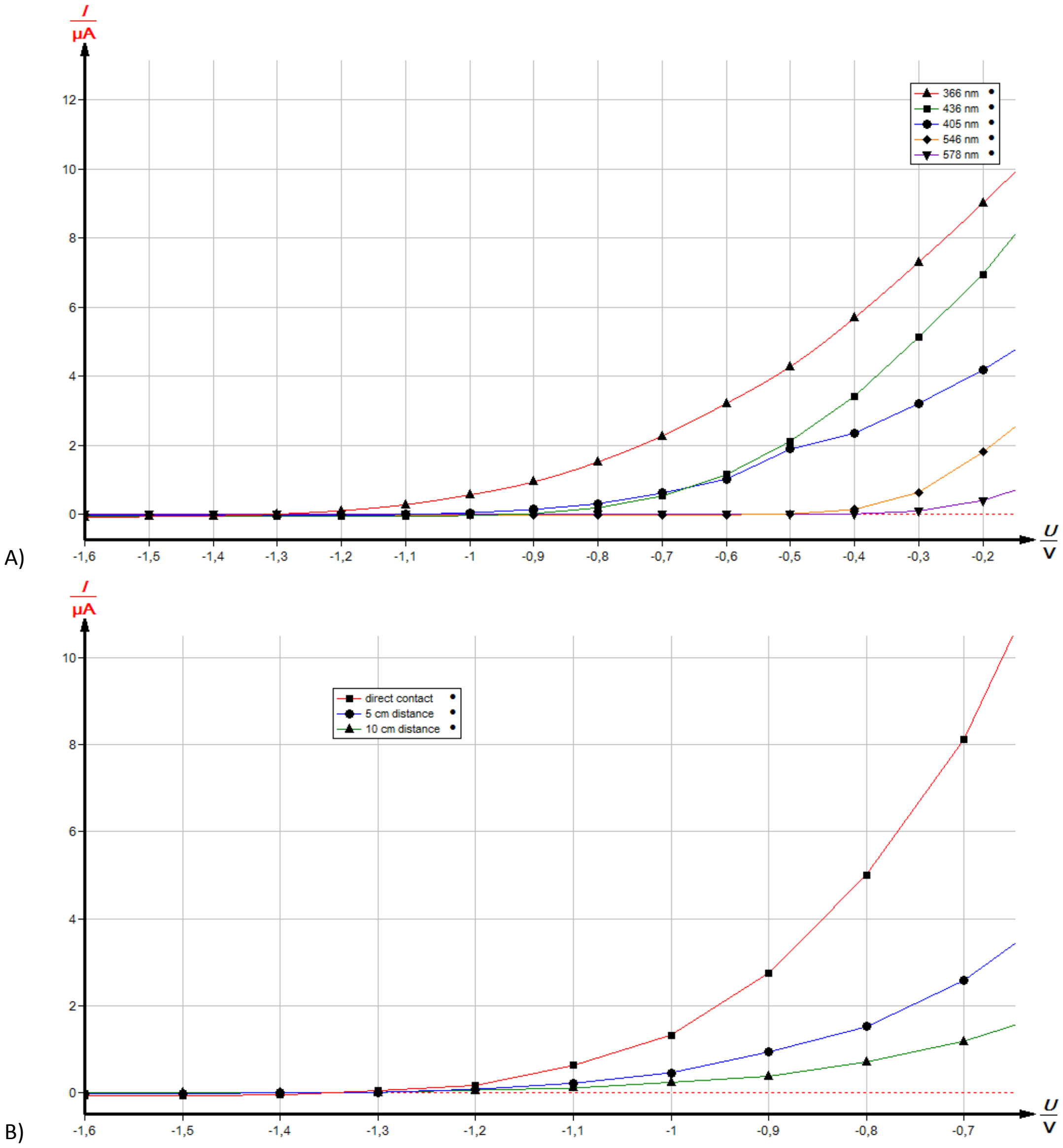


Fig. 3: The photoelectric current intensity I as a function of the bias voltage: A) at different frequencies of the irradiated light, B) at different intensities (constant wavelength: 436 nm).

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 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}):

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

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 = $1.602\cdot10^{-19}$ As gives their corresponding work functions W_A and W_C equation (2) is equivalent to

$$e\,U_0 + W_A - W_C = W_{kin} \qquad (3)$$

To calculate Planck's constant h using the photoelectric effect, we compare (2) with Einstein equation (1):

$$W_{kin} = e\,U_0 + W_A - W_C = h\,f - W_C \qquad (3)$$

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

$$eU_0 = hf - W_A \qquad \text{or}$$
$$U_0 = \frac{h}{e} f - U_A \qquad (4)$$

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 $f = c / \lambda$ with speed of light c = 299 792 458 m/s.

The measured slope is:

$$0{,}00366 \ \frac{V}{10^{12}\frac{1}{s}}$$

Multiplication with e gives: $h = 5{,}59\ {}_{.}\ 10^{-34}$ Js

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

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.

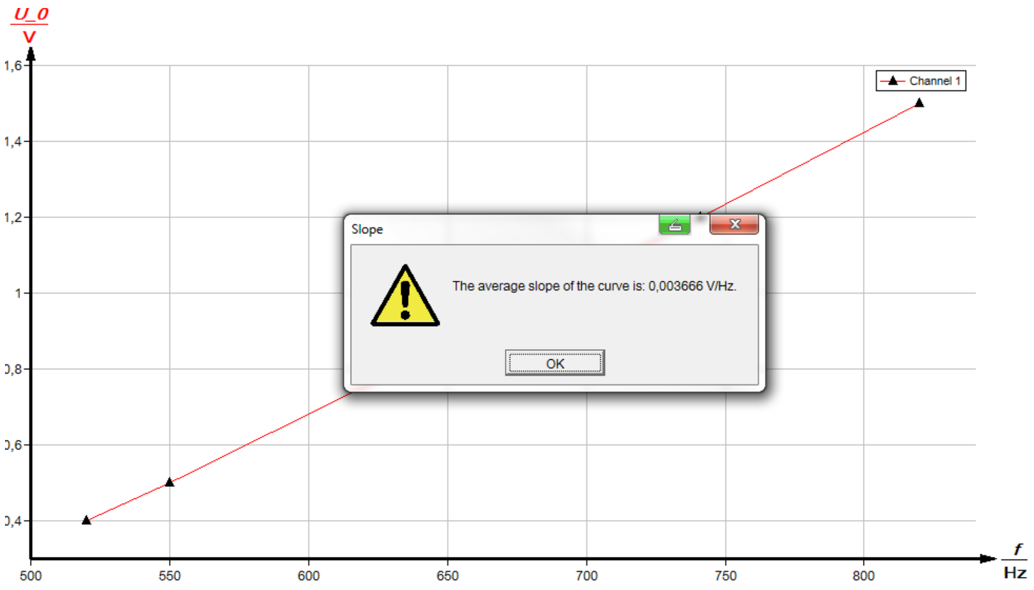
The cathode work function on the other hand determines whether the photon energy is sufficient to liberate an electron from the cathode. Historically, this photoeffect threshold wavelength was also important for the discovery of this effect and only later was understood when the electron energy spectrum 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



The average slope of the curve is: 0,003666 V/Hz.

Fig. 3: Stopping voltage U_0 as a function o the frequency of the irradiated light.

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.