

Determining Planck's constant

Selection of wavelengths with interference filters on the optical bench

Objects of the experiment

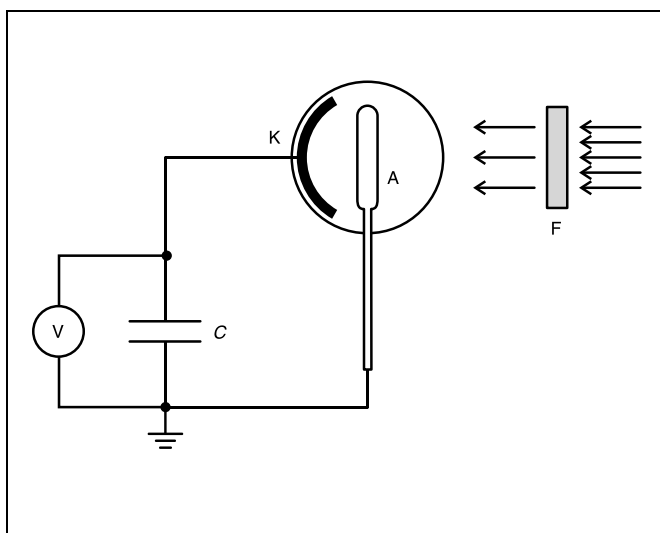
- To verify the photoelectric effect.
- To measure the kinetic energy of the electrons as a function of the frequency of the light.
- To determine Planck's constant h .
- To show that the kinetic energy of the electrons is independent of the intensity of the light.

Principles

Electrons can be liberated from the surface of certain metals by irradiating them with light of a sufficiently short wavelength (photoelectric effect). Their energy depends on the frequency ν of the incident light, but not on the intensity; the intensity only determines the number of liberated electrons. This fact contradicts the principles of classical physics, and was first interpreted in 1905 by Albert Einstein. He postulated that light consists of a flux of particles, called photons, whose energy E is proportional to the frequency:

$$E = h \cdot \nu \quad (I)$$

Fig. 1 Schematic representation of an experiment for measuring Planck's constant h with the aid of the photoelectric effect. Monochromatic light (produced by wavelength filter F) falls on cathode K of a photocell. The photoelectrons stimulated here travel to anode A and charge capacitor C up to the limit voltage U_0 .



The proportionality factor h is known as Planck's constant, and is regarded as a constant of nature. In this particulate conception of light, each photoelectron is replaced by a photon and exits the atom with the kinetic energy

$$E_{\text{kin}} = h \cdot \nu - W_K \quad (II)$$

where W_K is the work function of the electrons. It is independent of the irradiated material.

We can determine Planck's constant h by exposing a photocell to monochromatic light, i. e. light of a specific wavelength, and measuring the kinetic energy E_{kin} of the ejected electrons.

Fig. 1 shows a schematic representation of such an experiment. The light falls through an annular anode, here a platinum wire, onto a potassium surface. Thanks to its low work function – the valence electrons of alkali metals are weakly bound – potassium is a very suitable cathode material.

Some of the ejected photoelectrons travel to the anode, where they are registered in the form of a photoelectric current I . If the photoelectrons are ejected against a negative potential which is gradually increased, the photoelectric current continually decreases. The voltage at which the photoelectric current reaches precisely zero is called the limit voltage U_0 . At this level, even the electrons with the weakest bonds, i. e. those with the lowest work function W_K and thus the greatest kinetic energy, can no longer overcome the anode voltage. In this experiment, the anode voltage is generated using a capacitor which is charged by the incident electrons up to a limit voltage U_0 (see Fig. 1). We can use this limit voltage U_0 to calculate the kinetic energy of these weakly bound electrons:

$$e \cdot U_0 = h \cdot \nu - W \quad (III)$$

e : elementary charge

Here, W is no longer the work function W_K of the cathode, as the contact potential between the cathode and the anode is included in the energy balance.

Apparatus

1 Photo cell for determining Planck's constant	558 77
1 Basic device for photo cell	558 791
1 High pressure mercury lamp	451 15
1 Lamp socket E27 on rod for high-pressure mercury lamp	451 19
1 Universal choke, in housing, 230 V, 50 Hz .	451 30
1 Lens in holder, f = + 100 mm	460 03
1 Iris diaphragm in holder	460 26
1 Filter revolver	558 792
1 Interference filter 578 nm	468 401
1 Interference filter 546 nm	468 402
1 Interference filter 436 nm	468 403
1 Interference filter 405 nm	468 404
1 Electrometer amplifier	532 14
1 Plug-in unit 230 V AC/12 V AC	562 791
1 STE capacitor, 100 pF, 630 V	578 22
1 STE key switch (N.O.)	579 10
1 Voltmeter, DC e.g.	531 100
1 Optical bench with standard profile, 1 m . .	460 32
or	
1 Auxiliary bench w. swivel joint 0.5 m	460 34
2 Optics riders, height: 90 mm, width: 50 mm	460 352
3 Optics riders, height: 120 mm, width: 50 mm	460 357
2 Clamping plugs	590 011
1 Straight, BNC	501 10
1 BNC adapter for 4-mm socket, 1-pole	501 09
1 Coupling plug	340 89
1 Distribution box	502 04
Connecting leads	

The measurements are conducted for various wavelengths λ and frequencies

$$\nu = \frac{c}{\lambda} \tag{IV}$$

c: speed of light in a vacuum

of the incident light. When the frequency of the incident light increases by $\Delta\nu$, the electron energy increases by $h \cdot \Delta\nu$. The limit voltage must be increased by ΔU_0 to compensate for the rise in the photoelectric current.

Safety notes

The high pressure mercury lamp also emits light in the UV range, and can thus damage the eyes.

- Never look into the direct or reflected beam of light from the high pressure mercury lamp.
- Observe the Instruction Sheet for the high pressure mercury lamp.

When we plot the limit voltage $U_0(\nu)$ as a function of ν , equation (III) gives us a straight line with the slope:

$$\frac{\Delta U_0}{\Delta \nu} = \frac{h}{e} \tag{V}$$

For a known elementary charge e , this gives us Planck's constant h .

In this experiment, narrow-band interference filters are used to select the wavelengths; each filter selects precisely one spectral line from the light of a high-pressure mercury lamp. The wavelength specification on the filter refers to the wavelength of the transmitted mercury line.

Setup

Optical setup:

Note: The high-pressure mercury lamp reaches its full intensity after a ten-minute warm-up period.

Switch on the high-pressure mercury lamp when you begin setting up the experiment, so that you can start measuring as soon as you are finished.

Fig. 2 shows the experiment setup; the position of the left edge of the optical riders is given in cm.

- Connect the universal choke to the mains via the distribution box.
- Mount the high-pressure mercury lamp at the marked position using an optical rider (H = 90 mm), connect it to the universal choke and switch it on.
- Mount the photocell at the marked position using an optical rider (H = 90 mm); remove the cover and align the photocell so that the coated black surface is facing the mercury lamp.
- Mount the iris diaphragm on the optical bench at the marked position using an optical rider (H = 120 mm).
- Mount the lens at the marked position using an optical rider (H = 120 mm) and adjust its height so that the center of the lens is at the same height as the center of the iris diaphragm.

The light from the mercury lamp should now produce a sharp light spot on the black coating (the sensitive area) of the photocell. The light should not fall on the metal ring nor on the part of the black-coated area to which the contacts are attached. The edge zones should not be illuminated either.

To ensure that this is so, carry out the following procedure, repeating as often as necessary to produce the optimum image:

- Vary the height of the iris diaphragm and the lens so that the light spot falls on the black zone of the photocell; make sure that the center of the lens is always on the same level with that of the iris diaphragm. You may also need to adjust the height and inclination of the photocell (using the screws below the base).
- Using the iris diaphragm, adjust the size of the light spot so that it illuminates the largest possible area of the black zone of the photocell, without shining on the outer zones, the metal ring or the contacts on the black coating.
- Focus the light spot as necessary by moving the lens along the optical bench.

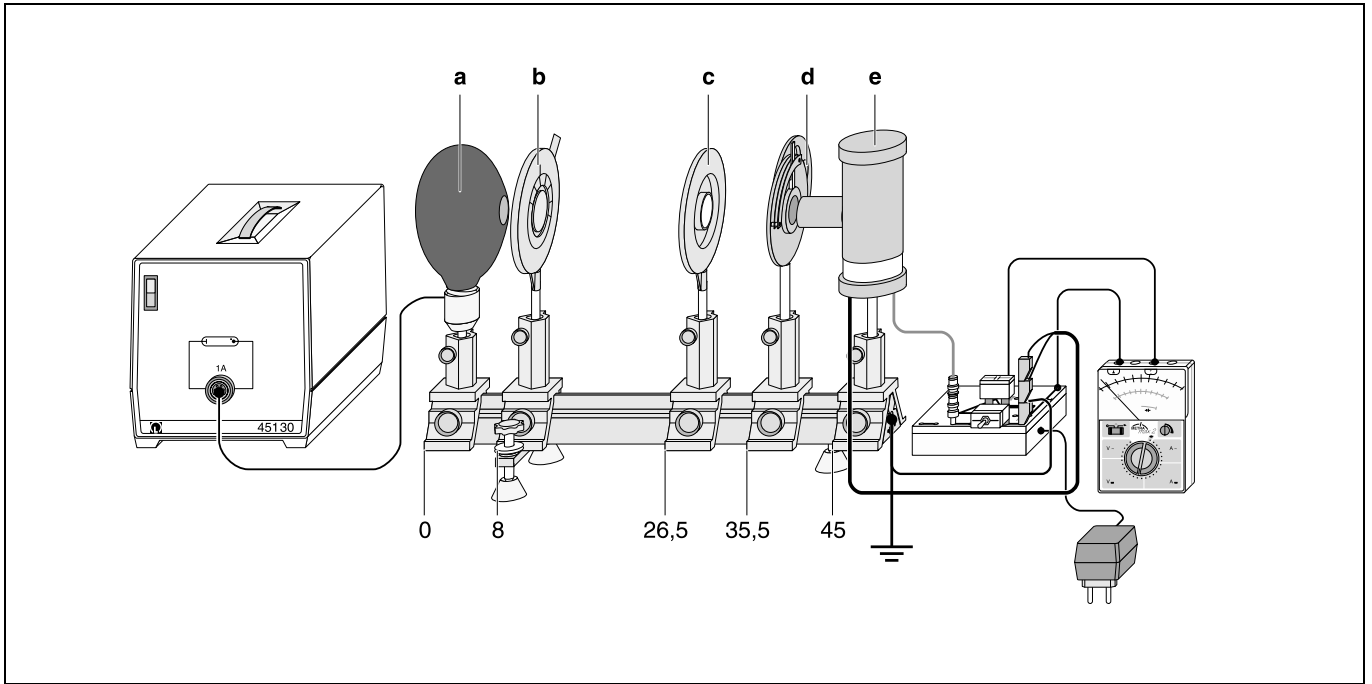
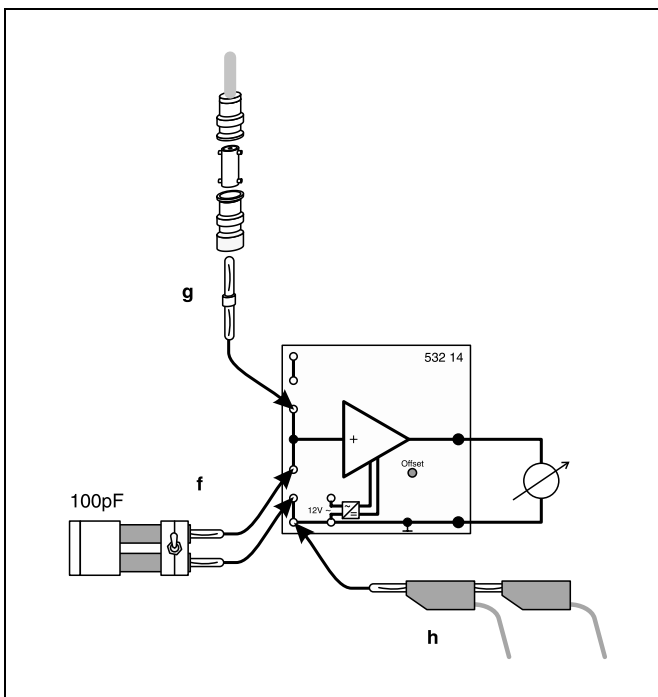


Fig. 2 Experiment setup on the optical bench with positions in cm for the left edge of the optical riders.
a high pressure mercury lamp
b iris diaphragm
c lens, $f = 100$ mm
d revolver with interference filters
e photocell

Note: once you have adjusted the experiment setup, be sure not to change the setup again.

- Place the cover on the photocell.
- Place the filter revolver with iris diaphragm directly in front of the photocell using an optical rider ($H = 120$ mm) and connect the iris diaphragm of the filter revolver with the cover of the photo cell to prevent scattered light from reaching the photocell.

Fig. 3 Electrometer amplifier circuit for measuring the limit voltage U_0



Electrical assembly:

The photoelectrons incident on the metal ring of the photocell charge a capacitor, generating the limit voltage U_0 required for determining the kinetic energy. The electrometer amplifier is used to measure the voltage at the capacitor.

Set up the electrometer amplifier circuit as shown in Fig. 3.

- Attach terminal plug (**f**) and connect the 100 pF capacitor and the key switch.
- Attach coupling plug (**g**), the BNC/4 mm adapter and the straight BNC and connect these to the gray screened cable of the photocell.
- Connect both black cables (**b**) of the photocell to the ground connection on the electrometer amplifier.
- Connect the multimeter to the output of the electrometer amplifier.

Also:

- Connect the plug-in supply unit (12 V) to the electrometer amplifier and plug it in via the distribution box.
- Connect the optical bench (and possibly the rod of the basic device of the photocell) to the ground connection of the electrometer amplifier, and connect this terminal to the external ground of the distribution box.

Carrying out the experiment

Notes:

If potassium from the light-sensitive layer of the cathode becomes deposited on the anode ring, this can cause an electron flux which will interfere with the experiment.

If necessary, bake out the photocell as described in the Instruction Sheet.

Dirt on the photocell can cause leakage currents between the anode and the cathode which can affect the measurement of the limit voltage U_0 .

Clean the photocell with alcohol.

The voltage at the capacitor can be influenced by induction effects.

Move this part as little as possible during the experiment.

You do not need to darken the room; this has no effect on the measurement results.

- Switch on the multimeter and set the range switch to 1 V DC.
- Turn the interference filter for yellow light ($\lambda_{Hg} = 578 \text{ nm}$) into the beam path.
- Discharge the capacitor by holding down the key switch until the multimeter reads zero V.
- Start the measurement by releasing the key switch; wait about 30 s to 1 minute, until the capacitor has charged to the limit voltage U_0 . Write down the measured value for U_0 .
- Turn the interference filter for green light ($\lambda_{Hg} = 546 \text{ nm}$) into the beam path and repeat the measurement.
- Extend the measuring range to 3 V and repeat the measurement with the blue ($\lambda_{Hg} = 436 \text{ nm}$) and violet ($\lambda_{Hg} = 405 \text{ nm}$) interference filters.
- Vary the intensity of the incident light at the photocell using the iris diaphragm of the filter revolver and measure the limit voltage U_0 for each setting.

Note: If the iris diaphragm is closed too far, this may affect the uniform illumination of the light spot on the cathode. Also, leakage currents will play an increasing role.

Measuring example

Table 1: Limit voltage U_0 as a function of the wavelength λ and the frequency ν .

Color	$\frac{\lambda}{\text{nm}}$	$\frac{\nu}{\text{THz}}$	$\frac{U_0}{\text{V}}$
Yellow	578	519	0.59
Green	546	549	0.70
Blue	436	688	1.23
Violet	405	741	1.40

Evaluation

Fig. 4 shows the limit voltage U_0 as a function of the frequency ν . The plotted measurement points lie on a straight line with close approximation.

A line fitted to the first three measurement points has a slope of

$$\frac{\Delta U_0}{\Delta \nu} = 0.38 \cdot 10^{-14} \text{ Vs}$$

According to (V), it follows from $e = 1.6 \cdot 10^{-19} \text{ As}$ that the value of Planck's constant is

$$h = 6.1 \cdot 10^{-34} \text{ Js}$$

Literature value: $h = 6.62 \cdot 10^{-34} \text{ Js}$

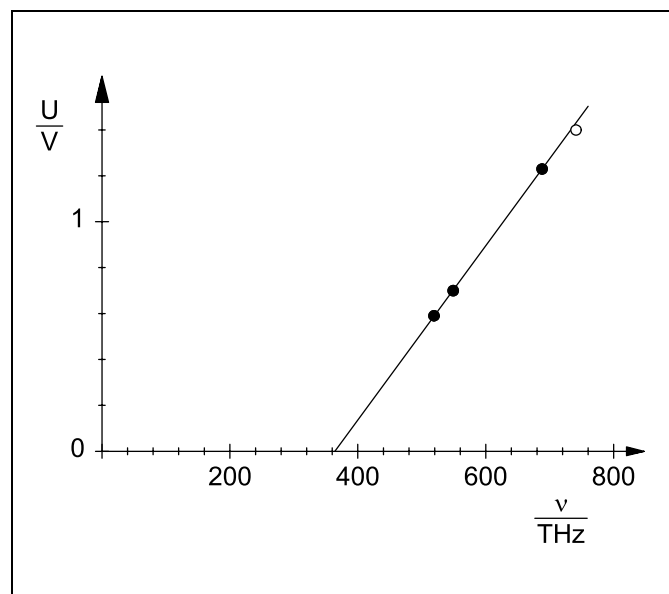


Fig. 4 Limit voltage U_0 as a function of the frequency ν

Results

In the photoelectric effect, the kinetic energy E_{kin} of the liberated electrons depends on the frequency, and not on the intensity of the incident light.

Planck's constant h can be determined by measuring the limit voltage U_0 , above which the electrons can no longer escape, as a function of the frequency ν .