

Determining Planck's constant Counter voltage method

Objects of the experiment

- Record the voltage-current characteristic of a photocell.
- Measure the kinetic energy of the electrons as a function of the frequency of the light.
- Determine Planck's constant h

Principles

Light interacting with matter can transfer energy to surface electrons and light of a sufficiently short wavelength can even liberate them from the surface in certain metals (photoelectric effect). The energy of the electrons 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:

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

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 released by a photon and exits the metal surface with the kinetic energy

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

where W_K is the work function 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: 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 excited here travel to anode A against the counter voltage U_c and create a photocurrent I_p .

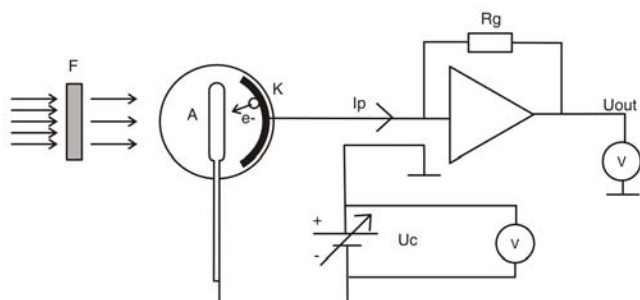


Fig. 1 shows a schematic representation of such an experiment. The light falls through an annular anode A, here a platinum wire, onto a potassium surface K. Thanks to its low work function—the valence electrons of alkali metals are weakly bound—potassium is a very suitable cathode material.

The photocathode K is held close to ground by the amplifier. There is an adjustable voltage U_c (the “counter voltage”) applied between anode and ground and therefore between anode and cathode, usually with the anode at a more negative potential than the cathode. Some of the ejected photoelectrons travel to the anode, and if the kinetic energy of the electron is larger than the energy loss while “climbing up” the potential $e \cdot U_c$, they reach the anode and are registered as a photoelectric current I_p .

The energy of an electron reaching the anode is:

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

e : elementary charge

Here, W is not only the work function W_K of the cathode, as additionally the contact potential between the cathode and the anode is included in the energy balance.

If the remaining energy of an electron is still positive it can reach the anode and contribute to the photocurrent, if the calculated energy would be negative, the electron will not reach the anode wire, but turn away and form an electron cloud in front of the cathode.

The voltage at which the photoelectric current reaches zero is in some other experiments called the limit voltage U_0 . In this experiment we record the total voltage-current dependency of the cell to make a better estimation of the limit voltages.

The current-voltage traces are recorded for various wavelengths λ and therefore frequencies

$$\nu = \frac{c}{\lambda} \quad (IV)$$

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 will then increase by ΔU_0 to compensate for the rise in energy. This increase is independent of the work

function as long as we use the same area of the photocathode.

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

$$\frac{\Delta U_0}{\Delta v} = \frac{h}{e} \quad (V)$$

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

In reality there are some more currents summing up to the measured photoelectric current: The true photoelectric current from the electrons released in the cathode is of course the main component, but there are also contributions from a so called dark current of ohmic behavior, and a very small

component of electrons traveling from the anode wire to the cathode, being released from the anode by stray light.

In total, these three currents sum up, so that at a sufficiently small negative potential there is a large current of electrons flowing from the illuminated cathode to the anode, which we call a positive current I_p . With increasing negative anode potential U_c , the photocurrent decreases exponentially and changes sign to a negative current, due to the leakage current effects discussed.

In this experiment, narrow-band interference filters are used to select the wavelengths; each of the five filters 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.

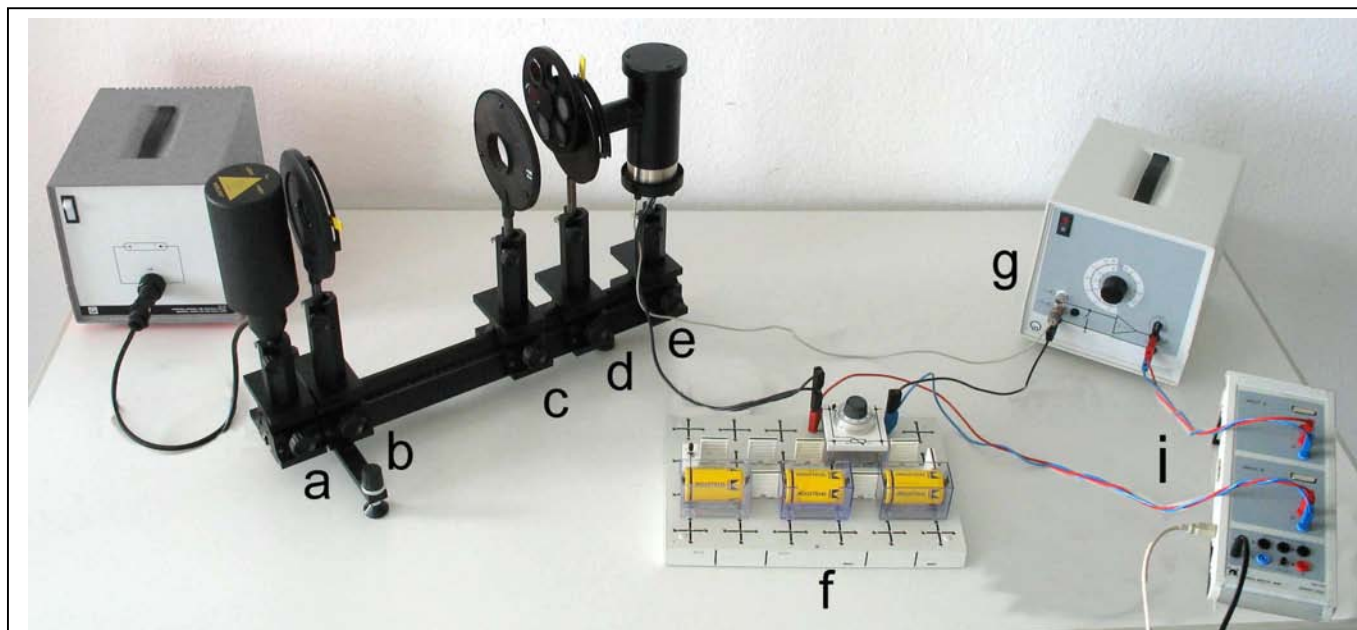


Fig 2: Setup of the experiment

| | | |
|---|--------------------------------|------------------------------------|
| a high pressure mercury lamp (on 60 mm rider) | b iris diaphragm (90 mm rider) | c lens, $f = 100$ mm (90 mm rider) |
| d revolver with interference filters(90 mm rider) | e photocell (60 mm rider) | f adjustable counter voltage |
| g photocurrent amplifier | i Sensor-CASSY | |

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. Do not start to record values while the lamp heats up.

Fig. 2 shows the experiment setup.

- Connect the universal choke to the mains.
- Mount the high-pressure mercury lamp (a) at the left end of the optical bench using an optical rider ($H = 60$ mm), connect it to the universal choke and switch it on.
- Mount the photocell (e) at the right end using an optical rider ($H = 60$ mm); remove the cover and align the photocell so that the blue-black coated surface is facing the mercury lamp.

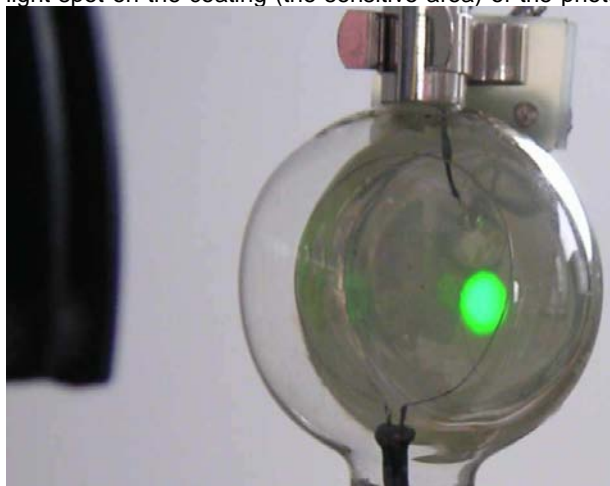
- Mount the iris diaphragm (b) on the optical bench close to the lamp using an optical rider ($H = 90$ mm).
- Mount the lens (c) in the middle of the optical bench using an optical rider ($H = 90$ mm) and adjust its height so that the center of the lens is at the same height as the center of the iris diaphragm. The exact position will be adjusted in the next step.

Safety notes

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

- Never look into the direct or reflected beam of light from the high pressure mercury lamp.
- Do not expose the skin to the light from the mercury lamp for longer than a few minutes
- Observe the Instruction Sheet for the high pressure mercury lamp.

The light from the mercury lamp should now produce a sharp light spot on the 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.

Note: Take care that the photocell remains clean, especially free from dust and grease, as these can become conductive, clean the outside if necessary.

To ensure good results, carry out the following procedure, repeating as often as necessary to produce the optimum image:

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 3 |
| 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 Interference filter 365 nm | 468 406 |
| 1 I amplifier D | 532 00 |
| 3 Monocell holder | 57686 |
| 3 Mono cell 1.5 V (IEC R20) | 68548 |
| 1 10-turn potentiometer, 1 kOhm, | 57793 |
| 1 Toggle switch, single-pole | 57913 |
| 1 Plug-in board A4 | 57674 |
| 1 Set of 10 bridging plugs | 50148 |
| or alternatively | |
| 1 Power supply 12 V DC | 521 49 |
| 2 Voltmeter, DC | e.g. 531 100 |
| or alternatively | |
| 1 Sensor-CASSY | 524010 S USB |
| 1 PC | |
| 1 Optical bench with standard profile, 0.5 m | 460 335 |
| 2 Optics riders, height: 60 mm, width: 50 mm | 460 373 |
| 3 Optics riders, height: 90 mm, width: 50 mm | 460 374 |
| 2 Clamping plugs | 560 011 |
| 1 Distribution box | 502 04 |
| Connecting leads | |

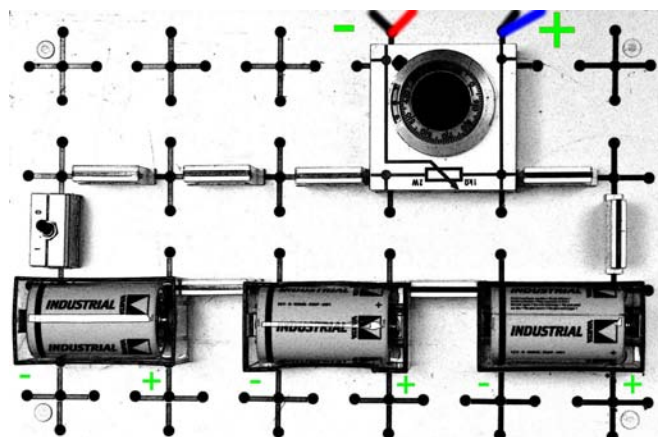
- Vary the height of the iris diaphragm and the lens so that the light spot falls on the blue-black zone of the photocell; make sure that the center of the lens is always on the same level with that of the iris diaphragm. You may also need to adjust the height and inclination of the photocell (using 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.

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 (d) with iris diaphragm directly in front of the photocell using an optical rider (H = 90 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.

Note: Instead of the optical setup described here (Interference filters) the same experiment can be done with the compact arrangement using a direct view prism or with a prism or grid on an optical bench.

Electrical assembly:



The photoelectrons incident on the metal of the photocell create a photocurrent which is amplified by the I measuring amplifier D and converted to a voltage. This voltage can then be read by a voltmeter or recorded by the computer, for example with a CASSY

Note: this experiment requires the use of a floating power supply, the plug-in board can be replaced by a power supply like 521 49, but any power supply with ground referenced outputs must not be used.

- Attach the gray screened cable of the photocell (e) to the measuring Amplifier D (g).
- Set up the STE plug-in board (f) with the batteries and the potentiometer as shown in the photo above.
- Connect both black cables of the photocell to the negative (-) output of the plug-in board, which is the wiper of the potentiometer.
- Connect the positive output (+) of the plug-in board to the ground connection of the measurement amplifier D (g), see Fig. 1 for the schematic diagram.
- Connect one multimeter or CASSY input A,U (not I) to the output of the measurement amplifier D and the other mul-

timer or CASSY Input B to the output of the plug-in board.

- If it is necessary to reduce electrical noise connect the optical bench (and possibly the rod of the photocell holder) to the ground connection of the measurement amplifier, in extreme cases connect this terminal to the external ground of the distribution box. Usually these connections are not required.

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.

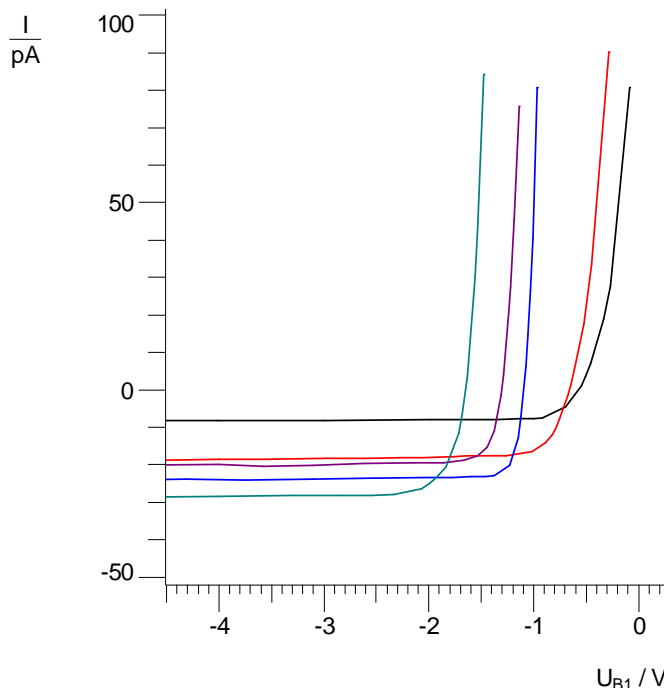
You do not need to darken the room; this has no effect on the measurement results.

- Switch on both multimeters and set the range switch to ± 10 V DC or start CASSYLab on the computer connected to the CASSY, select the 10 V range for both inputs A and B.
- Turn the interference filter for yellow light ($\lambda_{\text{Hg}} = 578$ nm) into the beam path.
- Set the potentiometer for the maximum counter voltage, something like -4.5 Volts.
- Observe the photocurrent, note that in the most sensitive setting of the I-Amplifier D the transimpedance R_g is 100 G Ω . So a photocurrent of 10 pA will be equivalent to 1V output. In CASSYLab create a formula for a Symbol "I", with Unit "pA" and the formula "UA1*10", meaning 1 V is worth 10 pA
- In CASSYLab, select "Measuring parameters / manual recording", and change the axis assignment to x-axis = "UB1", y-axis = "I"
- Adjust the setting of the iris behind the interference filter (d) to achieve approximately the same reverse photocurrent at all wavelengths, starting with a full open iris for the yellow line, as this is the weakest in intensity. If possible, do not vary the setting of the other iris (b), as this would change the illuminated area on the photocell.
- Reduce the counter voltage stepwise (for example in 0.5 V steps) and record the resulting photocurrent. When the photocurrent starts to rise, use smaller steps and wait before reading the values until the photocurrent has settled. In CASSYLab use "F9" to record one value.
- Turn the interference filter for green light ($\lambda_{\text{Hg}} = 546$ nm) into the beam path and repeat the measurement. In CASSYLab select "Measuring parameters / Append new meas. Series" to start a new curve in a different color.
- Repeat the measurement with the blue ($\lambda_{\text{Hg}} = 436$ nm), violet ($\lambda_{\text{Hg}} = 405$ nm) and ultraviolet ($\lambda_{\text{Hg}} = 365$ nm) interference filters.

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.

If there is no photocurrent at all observable, check if the photocell is fully screwed into the socket.

Measuring example

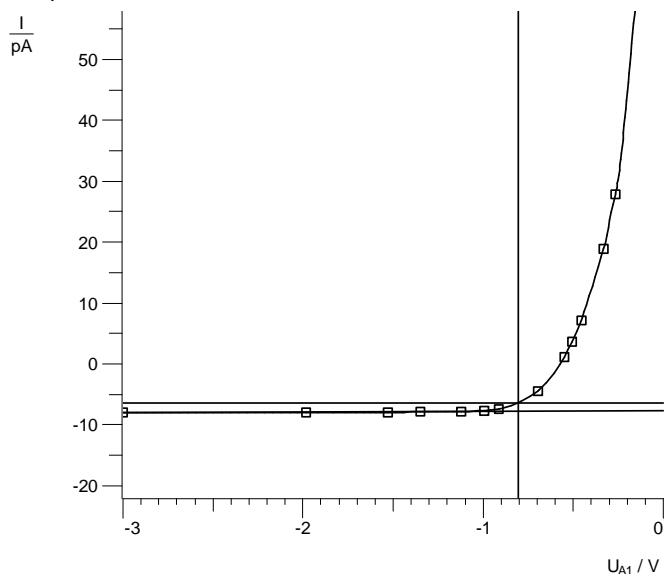


Below a sufficiently negative counter voltage, all the recorded curves show a constant current, which is independent of the counter voltage but depends on the intensity and wavelength of the incident light. This reverse current is generated by stray light on the anode ring. There is no ohmic component in this example, so the cell was clean of dust and dirt on the outside.

Depending on the wavelength of the incident light, the photocurrent starts to rise at different counter voltages. For the ultraviolet line, this happens at -2 Volt, for the yellow one at -0.6 Volt, and the other wavelengths in between.

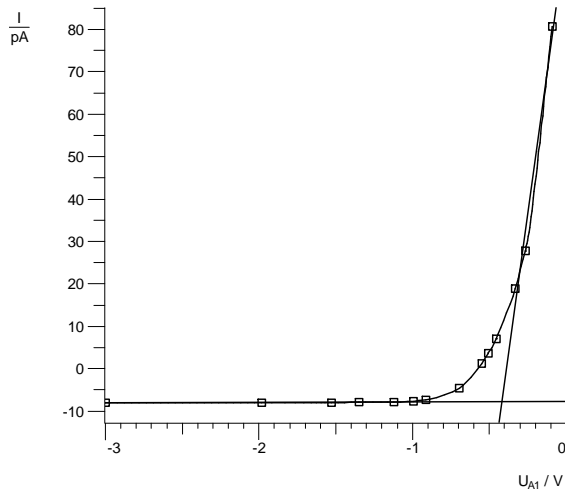
Evaluation

There are several ways in the literature to evaluate the measured data and determine at what counter voltage exactly the photocurrent starts.



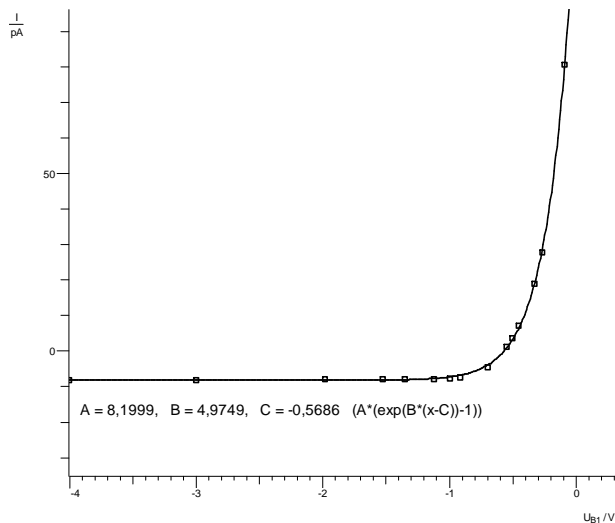
The easiest approach is to draw a line through all the measurement points on the left side before the photocurrent start, then draw a parallel line a few pA apart and take the crossing of the photocurrent with this line, in the image above at -0.81 V.

Another approach is to take again a best fit line through all the points on the left, and then another best fit line through all the data points at high photocurrents and look for the intersection of both lines, here at -0.4 V .



A third approach, which requires much more measurements, would measure the current-voltage curves for the same wavelength but at different intensities, and take the point where the curves intersect as “the” counter voltage, see [1]

A fourth, purely mathematical approach fits an exponential function to the measured values.



A function similar to Shockley's Diode equation $I(U) = A \cdot (e^{B \cdot (U-C)} - 1)$ is used, where A is the dark current, B somewhat related to light intensity times photocathode response and C is the counter voltage. In CASSYLab, press the right mouse key in the diagram, select “Fit function”, “Free fit”; in the dialog box type the formula “A*(exp(B*(x-C))-1)”, make some rough estimations for A(=10), B(=7) and C(=-1) and mark the data points to start the free fit. A few seconds later, CASSYLab will display the optimum values for A, B and C, and C is our result, where $I(C) = 0$. Therefore this evaluation is very similar to P6.1.4.3, in that experiment we are simply measuring the voltage where $I = 0$

In the end, all the different evaluations give quite similar results for Planck's constant as it is calculated only from the slope of the threshold voltage versus photon energy. Similar as the work function cancels out, so does any offset error from the data evaluation.

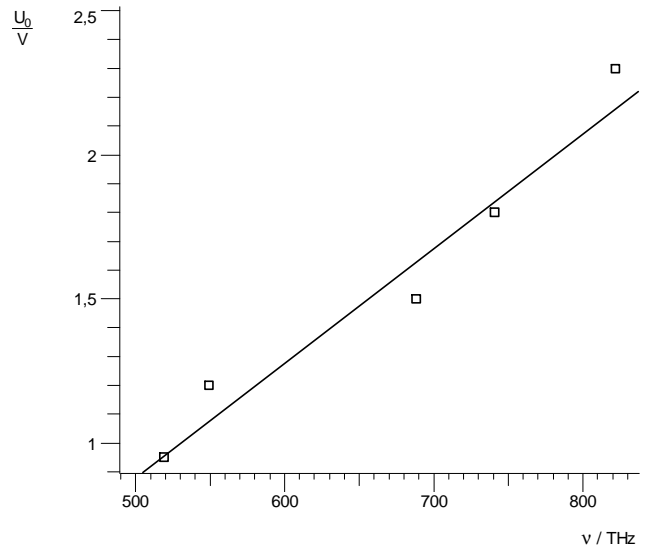
For simplicity we have chosen to use the first method described and look at the point where the photocurrent starts to

barely rise above the baseline on the left side of the diagram from the other currents.

This gives us the values of the limit voltage versus frequency of light:

| λ / nm | ν / THz | U_0 / V |
|-----------------------|--------------------|------------------|
| 578 | 519 | 0,95 |
| 546 | 549 | 1,2 |
| 436 | 688 | 1,5 |
| 405 | 741 | 1,8 |
| 365 | 822 | 2,3 |

Plotting the data in a diagram gives us this result



The plotted measurement points lie on a straight line with close approximation.

A line fitted to the measurement points has a slope of

$$\frac{\Delta U_0}{\Delta \nu} = 0,00398 \text{V/THz} = 3.98 \cdot 10^{-15} \text{Vs}$$

According to (V), multiplying with $e = 1.6 \cdot 10^{-19} \text{As}$ gives a value of Planck's constant

$$h = 6.37 \cdot 10^{-34} \text{Js}$$

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

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 .

Acknowledgment

Special thanks to Dr John Fry, Department of Physics, University of Liverpool for very helpful discussions and the idea of fitting with an exponential function.

References

[1] Langensiepen, Fritz; „Ein verbessertes Verfahren zur Bestimmung des Planckschen Wirkungsquantums mit in der Schule vorhandenen Mitteln.“; Praxis der Naturwissenschaften. Physik, 30 (1981) 11, S. 321-328

