PHOTOELECTRIC EFFECT

1. BACKGROUND INFORMATION

In 1887 the German physicist Heinrich Hertz experimented with the formation and propagation of electromagnetic waves. Investigating how sparks form between electrically charged plates, Hertz discovered that the sparks increased in intensity and quantity when the plates were exposed to ultraviolet light. Wilhelm Hallwachs, another German physicist, discovered in 1888 that a negatively charged zinc plate would lose its charge considerably more quickly when exposed to ultraviolet radiation. He attributed this phenomenon to the emission of negatively charged particles. The physicist Lenard discovered in 1900 that the ignition voltage of an electrical light arc decreased considerably when the negative electrodes were exposed to ultraviolet radiation, proving that these particles are electrons. In 1902 Lenard attempted to measure the energy required to remove electrons from photosensitive plates when the plates are exposed to light. In this connection he discovered a threshold voltage level below which no electrons could be removed from the plate, and that this threshold voltage did not depend on radiation intensity. He also discovered that the energy of the electrons after absorption was dependent on the colour of the light beam. In addition, he observed that no electrons could be absorbed from the plates using long-wave radiation, regardless of the intensity. The results of Lenard's experiments cannot be explained using the classic theory of light propounded by Maxwell. An ingenious explanation for these experimental findings was proposed by Albert Einstein in 1905. He assumed that the occurring radiation consisted of energy quanta, as proposed by Max Planck in his theory, which are proportional to the frequency of the radiation. Einstein determined the magnitude of the energy quantum to be *hf,* where *h* is Planck's universal constant and *f* the frequency of the radiation. The electrons emitted from the plate lose some of their energy, and this is referred to as the work function (Φ). The electrons emitted from the plate have a velocity *v* and thus an amount of kinetic energy expressed as $\frac{1}{2}mv^2$.

The energy equation resulting from Einstein's hypothesis is thus:

$$E = \frac{1}{2}mv^2 = hf - \phi$$

E = kinetic electron energy after emission
m = mass of the electron
v = velocity of the electron after emission
h = Planck's constant
f = frequency of the incident radiation
Φ = work function

This phenomenon became known as the (outer) **photoelectric effect**. For his ingenious explanation, Einstein was awarded the Nobel Prize in 1921 – not for his relativity theory, which at this time was still highly controversial.

Unconvinced by Einstein's explanation, the experimental physicist Robert Millikan conducted experiments to demonstrate that the theory was incorrect. Yet, after years of experiments, to his disappointment Millikan had to conclude that Einstein's assumption was indeed correct. In the course of these efforts he was able to determine Planck's constant to within an error level of 0.5%.

2. THE INNER PHOTOELECTRIC EFFECT

The **inner photoelectric effect** is the term for the phenomenon, discovered later, which occurs within semiconductors. When electrical energy is supplied to certain semiconductors, photons are released (LED) or, when photons impact the surface of other semiconductors, voltage is generated (photocells, photodiodes, phototransistors, photovoltaics etc.).

3. WHICH PHOTO EFFECT IS “BETTER”?

If either experiment can be performed just as easily, the outer photoelectric effect is clearly to be preferred for secondary or university students, since:

- The outer photoelectric effect is easier to explain and comprehend.
- Students can by means of the outer photoelectric effect additionally become acquainted with the important concept of work function.
- The outer photoelectric effect can be used to explicate the quantum nature of light along with Einstein’s simple yet ingenious explanation.
- The effect can be explained and demonstrated without any (or only insignificant) simplifications.
- Conditions within a semiconductor are more highly complex; many details need to be simplified in order make these processes understandable. Simplification easily leads to errors.
- Once the outer photoelectric effect has been grasped by performing the experiment, the inner effect will also be easier to explain.

4. THE CLASSIC EXPERIMENT

The cathode of a vacuum photodiode is exposed to light from a spectral lamp. The light beam is successively filtered using various selective filters, so that monochromatic light strikes the cathode each time.

When the energy of the electrons of the incident radiation is high enough (e.g. ultraviolet radiation), electrons (e-) are ejected from the cathode (photoemission). Possessing kinetic energy, these electrodes move to the anode of the photodiode. If we then connect the anode of the photocell with the cathode using a sensitive ammeter, we observe that, independent of light intensity, current (i.e. “**photocurrent**”) flows as a result of this arrangement. Now connect the cathode and the anode with a variable voltage source of reverse polarity, i.e. cathode positive (+) and anode negative (-) (see Fig. 1). When the voltage is gradually increased, the amount of photocurrent as measured by the ammeter (A) decreases and becomes zero below a certain voltage level as measured by the voltmeter (V). This voltage level, termed the “stopping potential” (V_{stop}), depends only on the cathode material and the wavelength of the radiation, not, however, on its intensity (Lenard’s experiments). The kinetic energy ($\frac{1}{2}mv^2$) required for an electron ejected from the cathode to reach the anode (i.e. to travel against the electrical field) is eV_{stop}.

This results in Einstein’s equation:

$$E = \frac{1}{2}mv^2 = eV_{stop} = hf - \phi \quad \text{(Equation 1)}$$

E = kinetic electron energy after emission
m = mass of the electron
v = velocity of the electron after emission
e = elementary charge ($e = 1.6 \text{ x } 10^{-19} C = 1.6^{-19} As$)
V_{stop} = stopping potential
h = Planck’s constant ($h = 6.626 \text{ x } 10^{-34} Js$)
f = frequency of the incident radiation
Φ = work function

The work function is therefore the minimum amount of energy required by a photon to remove an electron from the metal of the cathode. The magnitude of the work function is a property of the material and depends also on temperature.

Work function of certain metals:

Sodium	Φ = 2.06 eV
Potassium	Φ = 2.30 eV
Caesium	Φ = 2.14 eV

The relationship between V_{stop} and f is described by a linear equation, since e, h and Φ are constants. While this line is different for each metal, all lines have the same slope: $tg\alpha = h$.

The photodiode used here is a 1P39 vacuum diode with a cathode made of caesium. This model was used about 60 years ago for applications involving the visible range of light. As the work function of caesium is relatively low, even a beam of red light is capable of removing electrons from a caesium cathode. The work function for caesium is 2.14 eV at 0 °K and 1.95 eV at room temperature.

$$\underline{h = tg\alpha}$$

5. EXPERIMENT WITH THE APPARATUS PRESENTED ABOVE

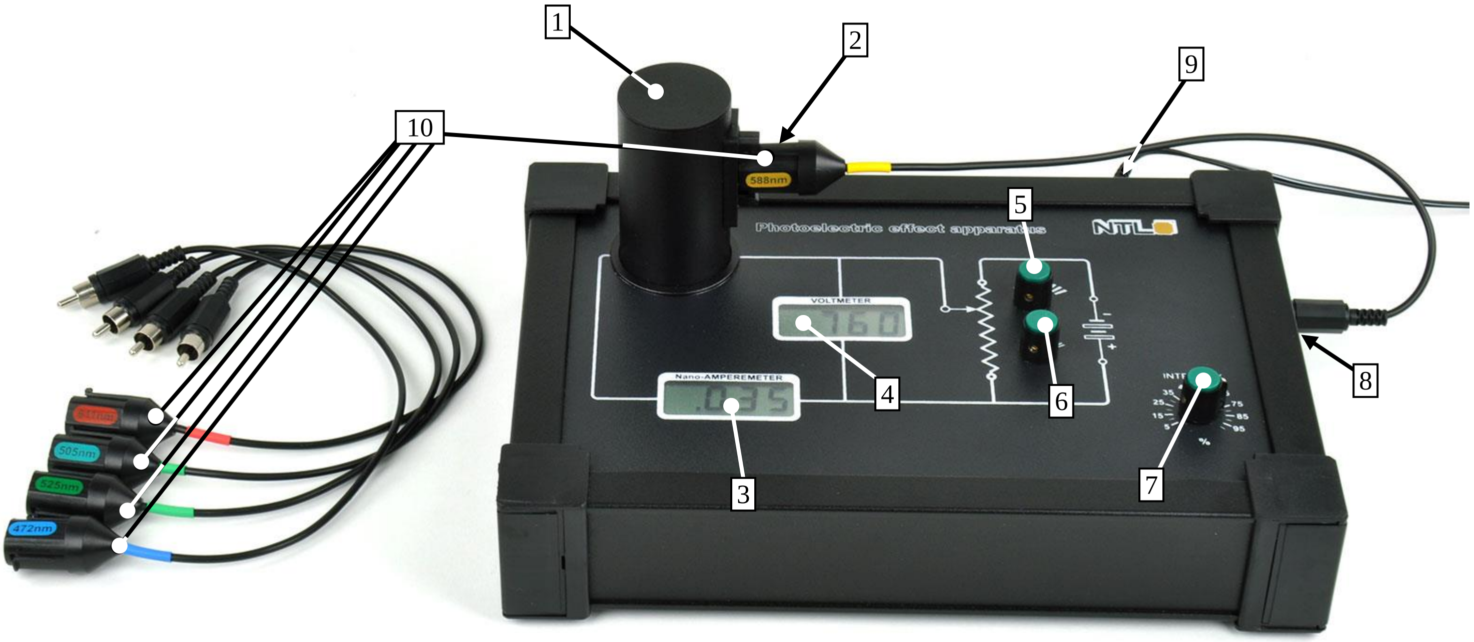
Using our apparatus, we will perform the classic experiment, i.e. demonstrating the outer photoelectric effect. A light beam that is highly monochromatic is required for photoelectric effect experiments, for both outer and inner effects. The method described above, involving a spectral lamp and selective filter, is expensive, time-consuming and, for secondary and university students, difficult to perform. To solve these problems, we have therefore chosen to use LEDs in five different colours as the light sources.

The beam emitted by an LED is shaped like a bell, whereas the full width at half maximum varies, depending on colour, from 15 nm to 37 nm. LEDs are therefore not necessarily monochromatic light sources (in the strict sense of the term). We have developed a method whereby the results derive from only the dominant (~ maximum) radiation wavelength emitted by the LED. In this way, the LEDs employed become monochromatic light sources.

A number of explanations can be found in the literature for why it is not possible to measure the work function using this kind of apparatus, in which the cathode and anode are connected and thus both Fermi levels reach the same amount of potential. However, we have also solved this problem in a simple way with our apparatus. There were also other problems that needed to be solved in order to enable the apparatus presented here to quickly and simply provide very accurate results. Yet we do not wish to go into these problems here.

6. IMPORTANT NOTES

- **Carefully read the operating instructions before using the equipment.**
- Replace any faulty fuse only with one having the same rating as the original.
- Do not place the apparatus on a surface exposed to shock or heavy vibration.
- Do not remove the protective cover of the vacuum photocell. Full exposure of the photocell to light causes it to wear quickly and will have a negative impact on functioning.
- Do not expose the device to extreme temperatures, humidity and moisture or direct sun’s rays.
- After completing the experiments, switch off the device and cover the light-conducting tube with the protective cap provided in order to protect the photocell from unnecessary wear.



7. DESCRIPTION OF DEVICE CONTROLS

(1) Protective cover for the photocell
(2) Light-conducting tube: the LED light sources are connected to this
(3) Nano-ammeter: sensitive instrument for measuring photocurrent
(4) Voltmeter for measuring stopping potential
(5) Dial for approximate adjustment of stopping potential
(6) Dial for fine adjustment of stopping potential
(7) Dial for setting light source intensity
(8) Socket for the light source
(9) Socket for the power supply
(10) LEDs with cable

8. PERFORMING THE EXPERIMENT

a. Connect the transformer to a mains socket (230 V/50 Hz) and then connect the output plug to the input socket (9). The device is ready to operate; the ammeter and voltmeter are switched on.

b. Switch the intensity to 75%.

c. Select the first light source, e.g. the red one, and connect it to the left side of the device.*

d. Completely insert the light source into the light-conducting tube.

e. Set the fine adjustment switch (6) to the centre position.

f. Gradually turn the approximate adjustment switch (5) until the ammeter shows a photocurrent reading of approx. zero.

g. Gradually turn the fine adjustment switch (6) until the ammeter shows a photocurrent reading of zero and the display **alternates between 0 and -0**.

h. Note the reading on the voltmeter. This is the stopping potential (V_{stop}) for this particular light source.

i. Proceed in the same way (from item c. on) with the other light sources.

* For the first measurement, it is recommended to wait a few minutes before setting the stopping potential.

9. RESULTS – ANALYSIS

Several methods exist for analysing the results. Four methods are described below:

9.1 THE CHART METHOD

The results for each of the colours (i.e. the five points) are entered in a coordinate system, in which case the x-axis is the frequency axis (*f*-axis) and the y-axis is the V_{stop}-axis. Finally, an attempt is made to connect the five points by means of an “optimally adapted” line.

Values for Φ and $h = \Phi/f_{min}$ can be derived from the diagram.
While this method is perhaps very easy to understand, the accuracy of the results depends on experience with the experiment.

9.2 THE MATHEMATICAL METHOD

Using the measured points, the optimum line is found by applying linear regression. Equation (1) is slightly adapted to become:

$$V_{stop} = \frac{h}{e} f - \frac{\phi}{e} \quad \text{(1.a)}$$

When $V_{stop} = y$ and $f = x$ are then inserted:

$$y = \frac{h}{e} x - \frac{\phi}{e} \qquad \text{(1.b)}$$

Whereas, according to the known method of linear regression, the following applies:

$$\frac{h}{e} = \frac{n.\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{\Delta}$$

$$\frac{\phi}{e} = \frac{(\sum_{i=1}^{n} x_i^2)(\sum_{i=1}^{n} y_i) - (\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} x_i y_i)}{\Delta}$$

and $$\Delta = n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2$$

This solution is obviously complicated and time-consuming. Yet there are pocket calculators which have this function pre-programmed, making this solution simple, fast and very accurate.

9.3 THE MODERN SOLUTION

The results are calculated using an EXCEL program (provided).

The readings for stopping potential are entered into the V_{stop} column of Table 1 Sheet 1.

NAME	λ [m]	Vstop [V]	f [Hz]	E = Vstop x e [J]	E = h x f - Φ [J]
	6.11E-07	0.087	4.91E+14	1.392E-20	1.334E-20
	5.88E-07	0.149	5.10E+14	2.384E-20	2.606E-20
	5.25E-07	0.445	5.71E+14	7.12E-20	6.663E-20
	5.05E-07	0.529	5.94E+14	8.464E-20	8.162E-20
	4.72E-07	0.663	6.36E+14	1.0608E-19	1.091E-19

Table 1

The line is then calculated automatically and displayed in Sheet 2.

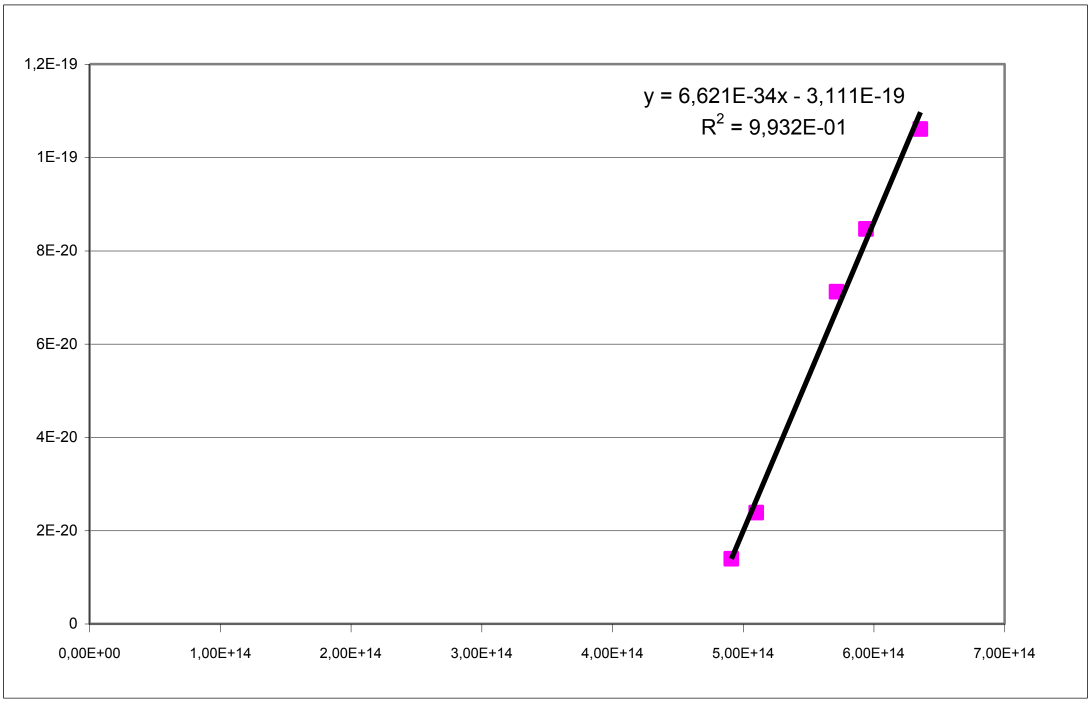


Figure 5

The values for *h* and *Φ* are obtained from the linear equation displayed in the top right of the figure.

These values are entered in Table 2 (Sheet 1) and the program then automatically calculates the deviation (error) from the theoretical values for *h* and *Φ*.

EXPERIMENTAL RESULTS	PLANCK'S CONSTANT [Js]	ELECTRON WORK FUNCTION [J]
THEORETICAL	6.626E-34	3.120E-19
MEASUREMENT RESULT	6.621E-34	3.111E-19
ERROR [%]	-0.08%	-0.29%

Table 2

9. CLEANING THE DEVICE

Remove the transformer plug from the socket in order to switch off the device before cleaning. Clean the device with a slightly moistened, lint-free cloth. Use only commercially available dishwashing detergents. Do not use any corrosive scrubbing powders. When cleaning, be careful to ensure that no liquids seep into the inside of the device. This could appreciably affect device functioning.

10. EXPERIMENTAL LIMITS OF THE DEVICE

At the beginning of the description, the experiments performed by Philipp von Lenard were mentioned. Are these experiments able to be duplicated? The answer is yes and no. If you wish to demonstrate that stopping potential is not dependent on the intensity of the light beam for example, you will discover that this is only true under certain conditions; a (small) dependence does in fact exist. There are a number of reasons for this, the most important being that the frequency of the LED light depends on the current flowing through the LED (according to the specifications of all manufacturers). This experiment can nonetheless be performed in an approximate manner by using the dial to vary intensity slightly from the recommended setting of 75%.

Yet no apparatus exists anywhere in the world which allows all of the experiments to be performed. The apparatus presented here is the only one in the world allowing very accurate results for Planck's constant and the work function of electrons in metals to be obtained very easily and very quickly. The level of precision for these two figures is < 5%. Beyond this, as already mentioned, Lenard's other experiments can also be performed approximately.

11. TECHNICAL SPECIFICATIONS

TECHNICAL SPECIFICATIONS		
Photocell	Material	Caesium (Cs)
Voltmeter	Display	3 1/2 Digit, LCD
	Precision	0.5% (typical)
Ammeter	Display	3 1/2 Digit, LCD
	Precision	1% (typical)
Dimensions	WxHxD = 280 mm x 120 mm x 160 mm	
Weight	approx. 1 kg	