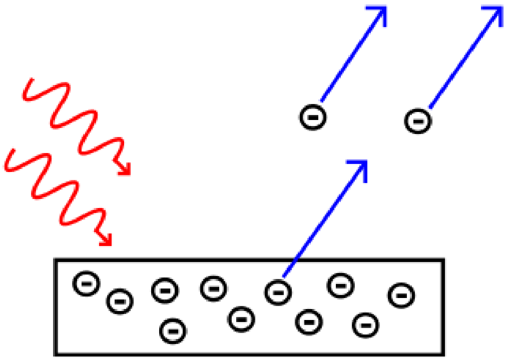
Photoelectric Effect

Study of the photoelectric effect

Lodovico Lappetito

Table of contents

The Photoelectric Effect



The **photoelectric effect** is the observation that many metals emit electrons when light shines upon them. Electrons emitted in this manner can be called **photoelectrons**.
According to classical electromagnetic theory, this effect can be attributed to the transfer of energy from the light to an electron in the metal. From this perspective, an alteration in either the intensity or wavelength of light would induce changes in the rate of emission of electrons from the metal. Furthermore, according to this theory, a sufficiently dim light would be expected to show a time lag between the initial shining of its light and the subsequent emission of an electron. However, the experimental results did not correlate with either of the two predictions made by classical theory.
Instead, electrons are only dislodged by the impingement of photons when those photons reach or exceed a **threshold frequency**. Below that threshold, no electrons are emitted from the metal regardless of the light intensity or the length of time of exposure to the light. To make sense of the fact that light can eject electrons even if its intensity is low, Albert Einstein proposed that a beam of light is not a wave propagating through space, but rather a collection of discrete wave packets (photons), each with **energy hf**. This shed light on Max Planck's previous discovery of the Planck relation **(E = hf)** linking **energy (E)** and **frequency (f)** as arising from quantization of energy. The factor **h** is known as the Planck constant :

$$E = hf = h(c/\lambda)$$

h is the Planck Constant
f is the frequency
λ is the wavelength
c is the light speed

In other words, the electron can leave the metal only if the energy of the photon is at least equal to the "work function" **($hf \geq W_e$)**. There exists, therefore, a **"minimum threshold"** of extraction for each metal, which is related to the wavelength (or frequency) of the incident photon and, therefore, to its energy **"hf"**, which coincides with the "extraction work" **(W_e)**.
The threshold value depends on the type of the considered material (generally metal) and depends, therefore, on its atomic characteristics; also the degree of purity of the metal affects the threshold value.
It should be emphasized that by increasing the intensity of the electromagnetic radiation (ie the number of photons per second, of equal energy, which affect the unit area) increases the number of electrons extracted but not their kinetic energy , which depends only on the energy of the incident photons .
This is a consequence of the quantum theory of Einstein, according to which every incident photon interacts with only a single electron.

The characteristics of the photoelectric effect are therefore as follows :

- there is a threshold frequency f_0 (said photoelectric threshold) , dependent on the type of metal, below which no emission is observed
- the kinetic energy of the emitted electrons is independent of the intensity of the incident radiation
- The number of emitted electrons (photoelectric current) increases with the intensity of the radiation
- The energy of single photoelectron increases as the frequency of the incident radiation

- the emission of photoelectrons is instantaneous for each value of the radiation intensity provided that $f > f_0$
- defining V_0 as the “stopping potential” for which $E_{kinmax} = eV_0$, V_0 is not dependent on the intensity I and grows linearly with the frequency of the incident radiation

The quantum interpretation of the photoelectric effect is the following :

- An electromagnetic radiation of frequency f carries packets of energy $E = hf$ called photons
- The intensity of the radiation is given by the number n of packets transported
- In the photoelectric effect a photon is completely absorbed by an electron, which increases its energy of an amount equal to hf
- The kinetic energy of the emitted electrons is $E_{cin} = hf - W_e$
    - W_e = energy required to extract an electron from the material
    - hf = energy provided by the radiation
- if $hf < W$ → there is not enough energy in order to extract electrons from the material → **photoelectric threshold**
- An electron can only receive energy from a quantum → the kinetic energy of the emitted electron does not depend on the intensity of the incident radiation
- increasing the intensity of the radiation increases the number of packets of energy → the number of emitted electrons increases with the intensity
- $E_{cin} = hf - W_e$ → the energy of the single electron increases as the frequency of the incident radiation

The photoelectric effect provides evidence, in a way not related to the blackbody radiation, that the electromagnetic radiation consists of quanta of energy hf.
NOTE: A photon can be absorbed only if its momentum is conserved - a free electron cannot absorb a photon and simultaneously conserving energy and momentum → thus is essential that the electrons are part of atoms.

These experimental facts can be easily verified by measuring the stopping potential V_0, which is the electrical voltage needed to stop the flow of electrons generated by the effect photoelectric :

$$E_{cin} = hf - W_e$$
$$E_{cinmax} = eV_0$$
$$V_0 = (hf - W_e)/e$$

The measurement should be made at different wavelengths.

Values of constants to be used :

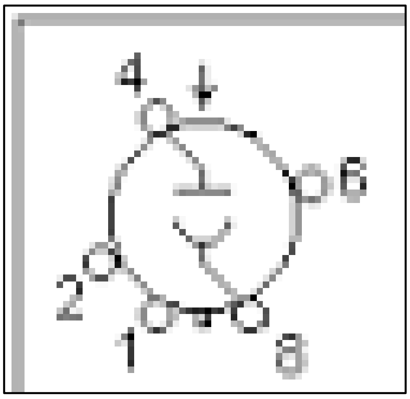
$$h = 6.626 \times 10^{-34}\ Js$$
$$e = 1.602 \times 10^{-19}\ C$$
$$h/e = 4.136 \times 10^{-15}\ Js/C$$

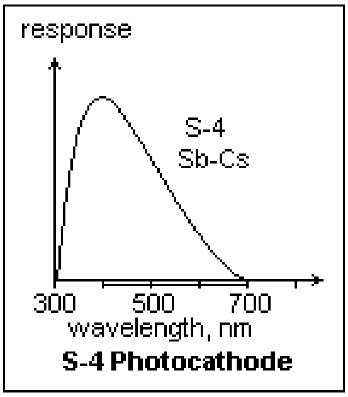
The Phototube 1P39

The phototube 1P39 is a vacuum tube with S-4 type spectral response.

Technical Data:
Spectral Response S-4
Wavelength of maximum response . . . . .4000 – 5000°A

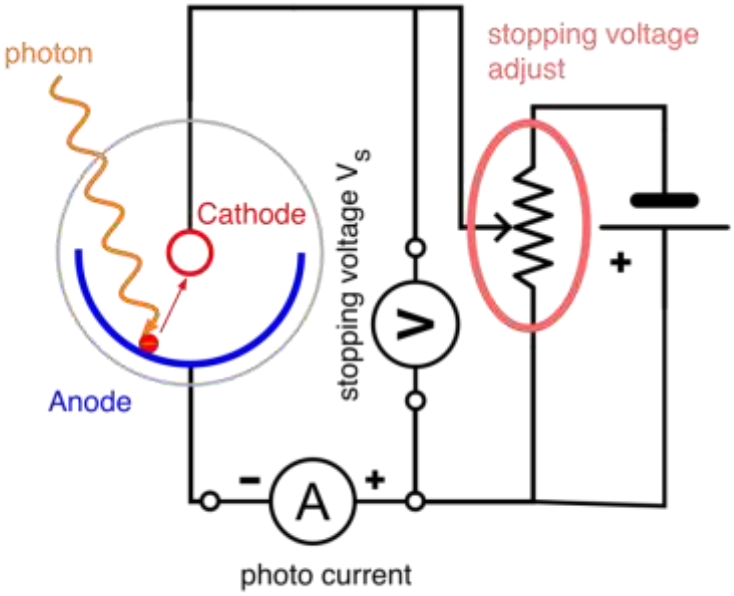
Cathode:
Bulb T9
Socket PentaPSK8CCM
Base . . . . Octal





Pin out of phototube 1P39 and spectral response of S-4 type photocatode

Experimental Setup

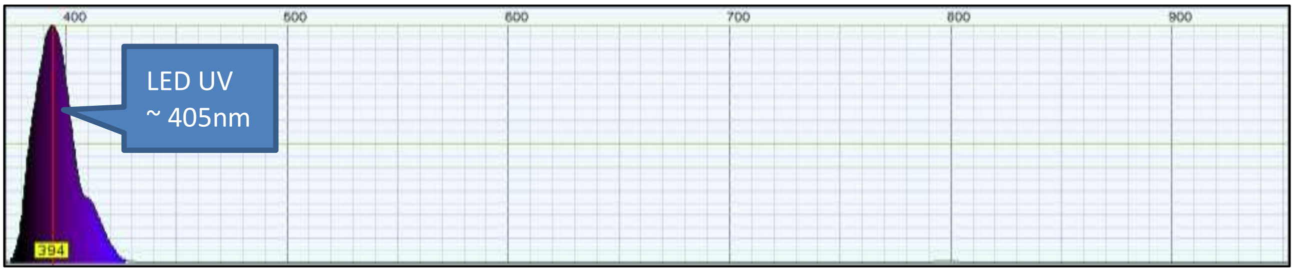


Schematic diagram of the experimental setup used for measuring the stopping voltage

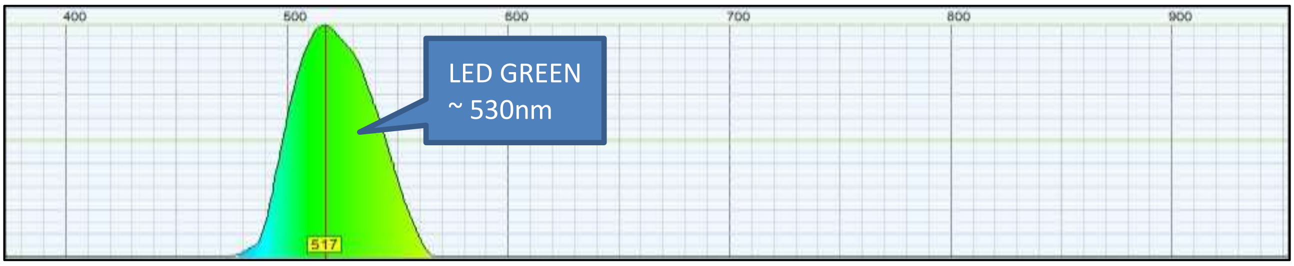
Phototube, potentiometer and pins for connections of measurement of stopping voltage and photocurrent

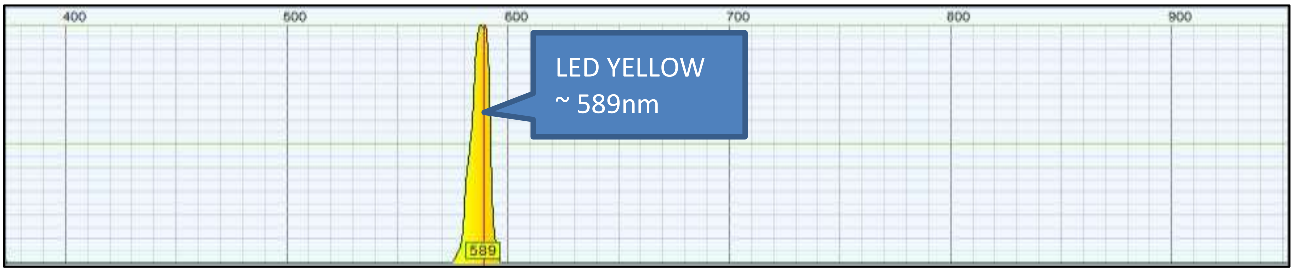
Phototube lid and LEDs for phototube lighting

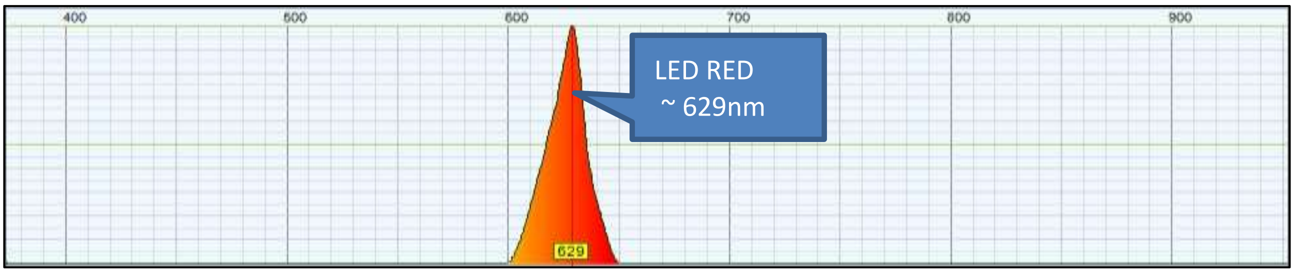
LED Spectra

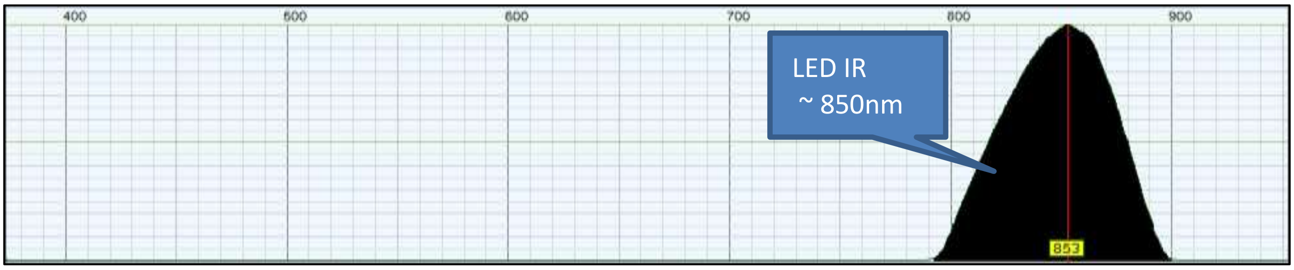

400
500
600
700
800
900
LED UV
~ 405nm
394


400
500
600
700
800
900
LED BLUE
~ 470nm
452

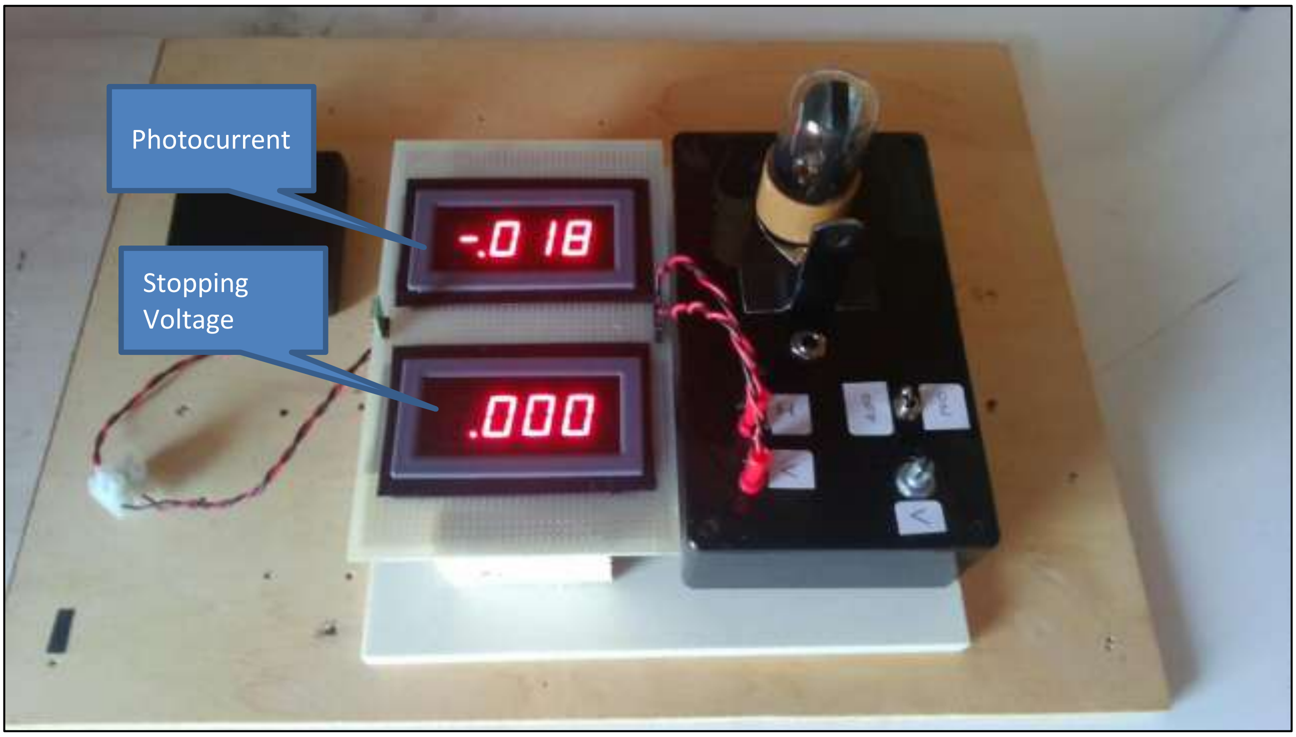

400
500
600
700
800
900
LED GREEN
~ 530nm
517

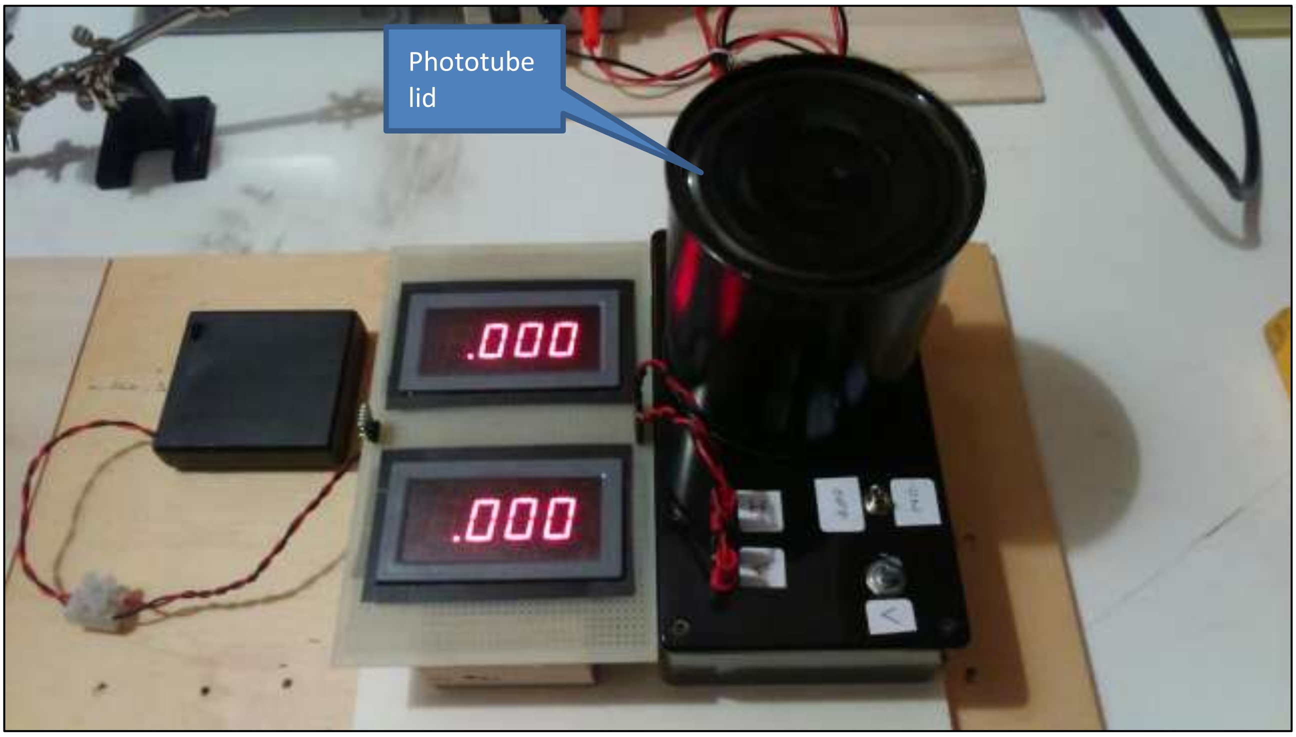

400
500
600
700
800
900
LED YELLOW
~ 589nm
589


400
500
600
700
800
900
LED RED
~ 629nm
629


400
500
600
700
800
900
LED IR
~ 850nm
853

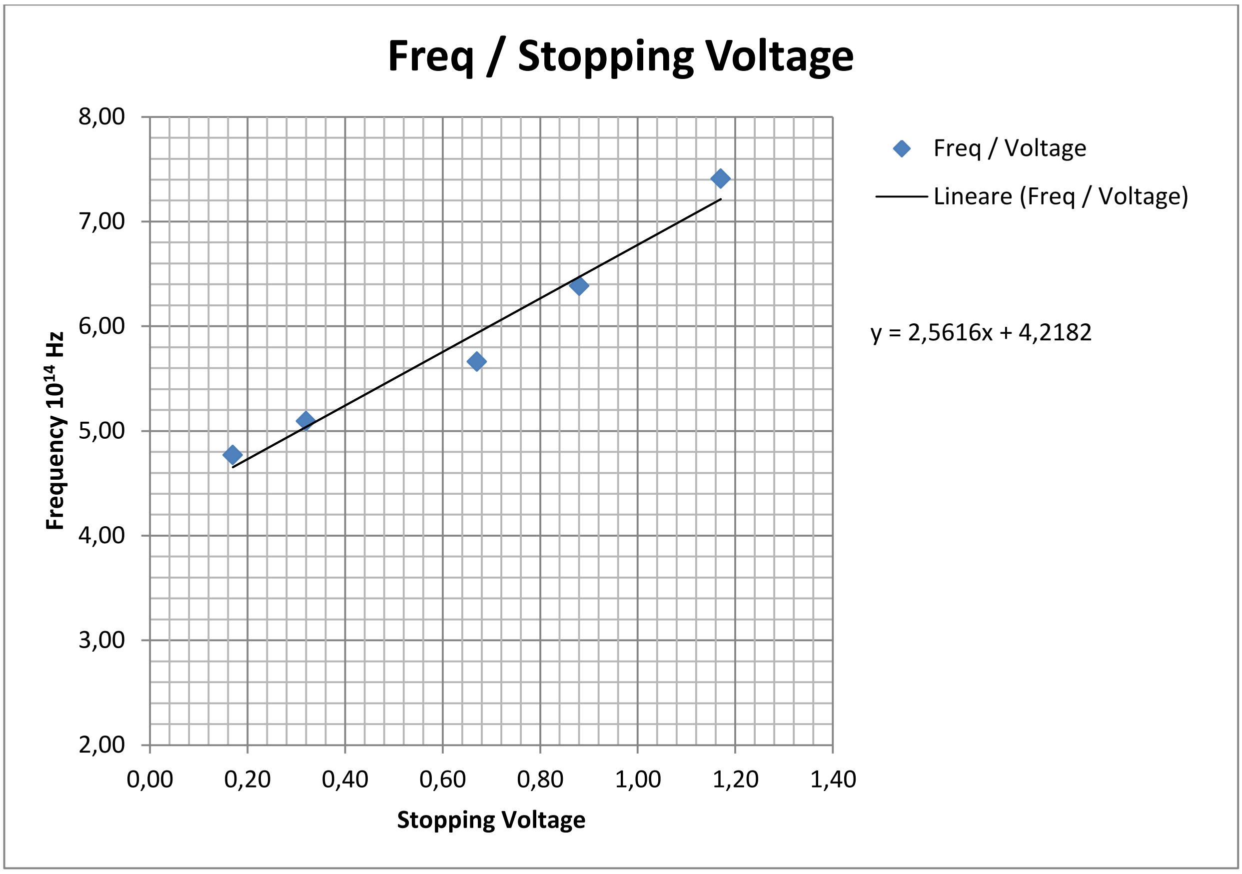
Measurements





The voltage between the anode and cathode of the phototube is adjusted with the potentiometer until the photocurrent is null. The voltage value at that point corresponds to the "stopping voltage". The measurement is repeated for all the types of LEDs. Infrared LED 850nm does not produces photocurrent.

LED Type	Wavelength (nm)	Frequency 10^{14}Hz	Stopping Voltage (V)
Infrared	850,00	3,57143	NA
Red	629,00	4,76948	0,17
Yellow	589,00	5,09338	0,32
Green	530,00	5,66038	0,67
Blue	470,00	6,38298	0,88
Violet	405,00	7,40741	1,17



From the linear regression of the above graph we obtain :

h/e = 3.9×10^{-15} Js/C (while the correct value is 4.136×10^{-15} Js/C)

$W_e = 4.218 \times h \times 10^{14} = 1{,}74$eV