The photoelectric effect

References

R.D. Knight: Physics for Scientists and Engineers: A Strategic Approach, Ch. 38 (Quantization), Pearson Education 2004

W. P. Garver: The Photoelectric effect Using LEDs as Light Sources, The Physics Teacher 44 (p.272-275), 2006

(1weight: Exercise 1; 2weights: all)

Introduction

The experiment that shattered the fundaments of classical physics was carried out by J.J. Thomson in 1899: he discovered that ultraviolet light discharges a negatively charged metal target. The target actually emits charges which were found to have the same charge/mass ratio as the electrons.

The emission of electrons from a material irradiated with light was named *the photoelectric effect*; emitted electrons are called *photoelectrons*.

Properties of the photoelectric effect

In 1900, Philip Lenard built an experimental setup to study the newly discovered photoelectric effect (Figure 1). He used a vacuumed glass tube with two electrodes and a window allowing light to shine on the cathode surface. Using an adjustable potential difference ΔV between the electrodes, Lenard measured a steady current in the outer circuit and drew a number of conclusions on the photoelectric effect properties:

- current I is proportional to the light intensity;
- current I appears without delay (in less than 0.1s)
- photoelectrons are emitted only if light frequency exceeds a threshold frequency f₀. The value of f₀ depends on the type of cathode metal.
- if the potential difference ΔV is made negative (anode negative with respect to the cathode), current I decreases until it becomes zero (at $\Delta V = -V_{stop}$). V_{stop} is called *stopping potential*. The value of V_{stop} is the same for intense and weak light.

Classical interpretation

Classical physics tried to explain the photoelectric effect by justifying the electron emission from a light-irradiated metal target by the thermal emission which occurs when a piece of metal is heated to high temperatures. In practice, thermal emission of electrons requires temperatures above 1500°C for most metals, when not only electrons are heated but also the crystal lattice, resulting into target melting.

Classical physics acknowledged that a minimum energy E_0 is needed to free an electron from a metal. E_0 is called *work function*.

The maximum kinetic energy of a photoelectron is given by: $K_{\text{max}} = E_{elec} - E_0$ (1)





In (1), E_{elec} is the electron energy inside the metal. The stopping potential corresponds to zero current (see Figure 1). Therefore:

$$V_{stop} = \frac{K_{\max}}{e}$$
(2)

Einstein's interpretation

In his famous 1905 paper, Albert Einstein postulated the quantization of electromagnetic radiation energy: each quantum of light has energy: E = hf (3)

In (3), $h = 6.63 \times 10^{-34} J \cdot s$ is Planck's constant; f is frequency of light. An electron can escape from a metal, becoming a photoelectron if: $E_{elec} = hf \ge E_0$

Combining (1), (2) and (3), we obtain Einstein's equation for the photoelectric effect: $eV_{stop} = hf - E_0$ (4)

According to (4), the stopping potential is a linearly increasing function of f:

$$V_{stop} = \frac{h}{e}(f - f_0) \tag{5}$$

A graph of V_{stop} vs. f would provide a way to measure Planck's constant h and *the cutoff* (or threshold) frequency f_0 .

Apparatus notes

The light source used in our apparatus consists of several interchangeable light emitting diodes (LED).

Figure 2 shows the experimental arrangement:



The phototube (PE) is shielded by a metal cage. The cage has to be grounded. The main controller has connectors for PE (in), ports for multimeters and a built-in potentiometer.

LEDs will be mounted on the power supply box in front of the PE. There are 8 diodes emitting from 390nm (UV) to 935 nm (IR), a variable intensity LED and an oscillatordriven LED. Some spectral widths are given below:

Color	λ (nm)	Δλ (nm)
UV	390	40
Blue	455	40
Cyan	505	30
Green	535	30
Amber	590	10
Orange		
Red	615	10
Red	640	10
IR	935	10

The stopping voltage

The experiment is performed using each LED as monochromatic light source. Using the built-in potentiometer, photocurrent can be adjusted to zero and thus the stopping potential can be measured (see Equation (2) above).

Is photoelectron emission dependent on light intensity?

Both photocurrent and stopping voltage can be measured at 4 light intensities using the variable intensity LED. According to the quantum theory, photoelectron energy will not depend on light intensity.

Time response of photocurrent

Using a function generator on square wave (as power supply), the oscillator-driven LED and an oscilloscope, observe the photocurrent variation and measure its time rise. A simple classical calculation will compare the power received by each electron from the photocathode material with the work function. The time needed by electrons to absorb light will be estimated.

Comparison with experimental data will show that in reality absorption of light is much faster, thus confirming the quantum theory.

The experiment

Exercise 1: The stopping voltage

Insert a LED into the power supply sockets and turn it on. Align the diode head with the PE window.

The two multimeters will be connected as voltmeters (remember that photocurrent is measured as potential drop across a $100k\Omega$ resistor).

With potentiometer on, decrease the photocurrent to zero and measure V_{stop} for each of the 8 wavelengths provided. The zero adjustment has to be checked up to the most sensitive meter range.

Estimate/calculate errors.

Graph V_{stop} vs. frequency of light (f) and determine the following quantities (Equation 5):

- Planck's constant h,
- Work function E_o,
- Cutoff (threshold) frequency fo

Note: in order to convince yourself that the infrared LED works, use the infrared detection and alignment card to visualize the beam.

Exercise 2: Light intensity effect

Use the variable intensity LED and independently measure V_{stop} and photocurrent (for V_{stop} use the potentiometer as in Exercise 1; for photocurrent potentiometer should be OFF).

Graph V_{stop} and Photocurrent vs Intensity. Intensity units are arbitrary. Comment the results.

Exercise 3: Photocurrent time response

Connect the PE to Ch1 of oscilloscope through the rectifying adaptor. **DO NOT TURN ON THE** PE **POWER SUPPLY.**

Connect the wave generator to the oscillator-driven LED and also to Ch2 of oscilloscope. Adjust the wave generator to square-wave frequency (in kHz) and amplitude in middle range. Adjust the oscilloscope to get 1-2 full periods of oscillation. If needed, use Acquire \rightarrow Average functions and the 20MHz filter.

Measure the transient photocurrent as a function of time and estimate the time constant.

The electric power consumed by the oscillator-driven LED is 60mW. Assume all this power is converted into light (P_{LED}). The photocathode area is A_{PC} = 3.23 cm². Each electron receives a fraction of the power P_e given by:

$$P_e = P_{LED} \frac{A_e}{A_{PC}} \tag{6}$$

Knowing that in solids electrons are \sim 0.3 nm from each other, calculate the energy absorbed by each electron in a second.

Using the work function determined in Exercise 1, estimate the time needed by an electron to absorb enough energy to escape the photocathode.

Compare with the experimental time constant, comment.

→ Python Requirements (PHY224/324 only): Do all the data analysis from Exercises 1-3 using Python. Output the required quantities with errors, goodness of the fit, plot the graphs.

This guide sheet was written in 2007 by Ruxandra M. Serbanescu. The experimental setup was built by Robert Smidrovskis.