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A "cost-effective" approach for the photoelectric effect experiment

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Abstract

A novel approach to investigating the photoelectric effect is proposed, it is affordable and accessible for any typical school laboratory. This cost-efficient measurement, using a series of digital multimeters, normally available in all the schools, facilitates the understanding of the photoelectric effect but also encourages creative problem-solving attitude among students and democratizes the access to quality physics education. By embracing this approach, schools which lack funds for expensive instrumentations can enrich their physics curriculum ensuring that every student has the opportunity to test the quantum nature of photons. The results of photoelectric effect measurements with this "cost-effective" approach, made by the students of the Liceo Scientifico Leondardo da Vinci of Trento, are presented. The inferred values of the Planck constant and of the work function are compatible with the ones obtained using the standard approach involving an "expensive" Galvanometer.

Keywords: *Photoelectric Effect; Planck constant; low-cost.*

1. Introduction

The photoelectric effect, first observed by Heinrich Hertz in 1887 and later elucidated by Albert Einstein in 1905, stands as a cornerstone in the field of modern physics. Teaching the photoelectric effect holds paramount importance in physics education, as it serves as a fundamental concept bridging classical and quantum physics and allows a laboratory measurement of the Planck constant, ***h***. Beyond its significance in theoretical physics, the photoelectric effect underpins numerous technological innovations and scientific advancements. From solar cells and photodetectors to digital imaging devices and spectroscopy techniques, the practical applications of the photoelectric effect permeate modern technology and scientific research.

The typical setup for the experiment of the photoelectric effect uses a light source, a set of monochromatic filters, a vacuum tube (photoelectric cell), a Galvanometer for current measurements and a tunable voltage source (see fig. 1). The laboratory measurement correlates the reverse voltage necessary to nullify the current in the circuit and the wavelength of the filtered light.

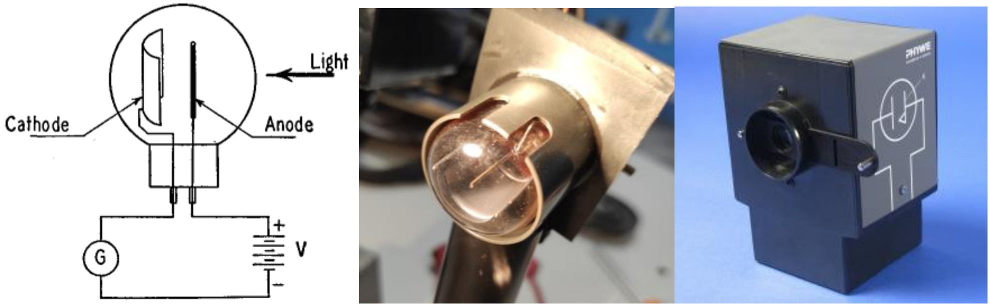

Figure 1. Drawing of the typical set-up for the photoelectric effect experiment (left). Pictures of the PHYWE-06778 PbS cell (center) and of the cell external housing (right).

In this experiment the sensitivity and internal resistance of the Galvanometer plays a crucial role. In particular, considering the intensity of a typical light source (avoiding damages related to excessive material heating) a current of few nA must be measured by the Galvanometer that should provide a negligible resistance in the circuit. The cost of such a device is not negligible, moreover the low internal resistance of the Galvanometer puts its integrity at risk in case of circuit mistakes during the assembling. For this reason an alternative approach for the measurement of Planck constant, ***h***, with the photoelectric effect experiment is proposed. This approach replaces both the Galvanometer and the variable voltage source with a series of identical digital voltmeters that are low-cost and rugged devices. Typically, a series of ~15 identical multimeters is available in most school laboratories to allow experiments related to the Ohm law and basic electromagnetism.

2. Measurement of the Photocell I/V curve

The idea is to replace both the Galvanometer and the tunable voltage source with a series of N voltmeters (see fig.2, bottom panel) and to characterize the I/V curve of the cell by varying N at fixed light intensity and wavelength. For our measurements we adopt the METEX M-4650 multimeters, setted at the lower scale, as a DC voltmeter. All of them are characterized by an inner resistivity of ~10MΩ, this can be verified by direct resistance measurements pairing the multimeters. Having a similar inner resistance, all the multimeters provide very similar voltage measurements in the series. The (loaded-) cell voltage, $\mathbf{V_{cell}}$, is obtained by summing the N multimeter voltage values. The current provided by the cell, $\mathbf{I_{cell}}$, is given by the average of the N multimeter voltages divided by the known average multimeter resistance. In the example shown in fig.2 bottom panel, $\mathbf{V_{cell}}$ = 394 mV and $\mathbf{I_{cell}}$ = 5.63±0.05 nA are measured. By adding or removing other multimeters in the series, part of the I/V curve of the cell can be traced.

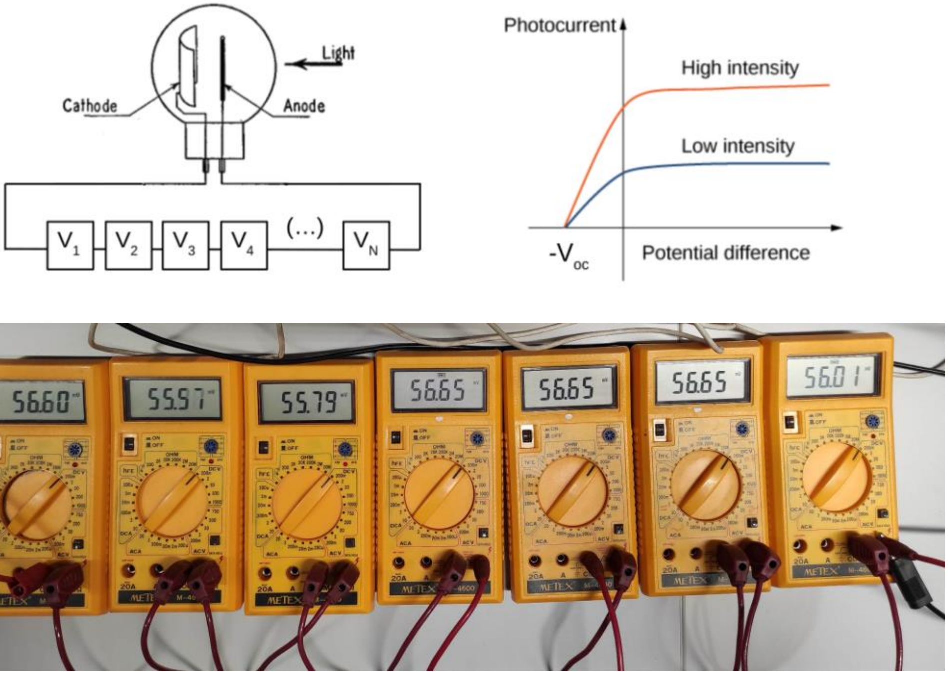

Figure 2. Drawing of the proposed set-up for the photoelectric effect experiment (left-picture). Expected behavior of the I/V characteristics for the photocell for a fixed light wavelength (right panel). An example of current and voltage measurement made with a series of 7 multimeters (bottom panel)

It is important to note that the exact knowledge of the average inner multimeter resistance is not really necessary for the photoelectric effect experiment. The uncertainty of the current measurement (mainly due to small departures of the internal resistance of each multimeter from the average one) can be inferred from the RMS of the values reported in the multimeter series. We found it is useful to take several pictures of the multimeters series during the experiment to minimize the measurement time, this allows to postpone the relatively slow data-entry process. The measurement has been taken with four filters selecting light with wavelengths of: 436, 546, 578 and 740nm. The I/V photocell characteristics, as measured by different student groups, are plotted in fig.3 (left plot) with colors: magenta, green, yellow and red, respectively. Different tonality of the same color in the data points plotted in fig.3 (left plot) marks different measurements using the same wavelength filter provided by different groups of students. It is important to note that the condition $\mathbf{I_{cell} = 0}$ cannot be tested directly due an high, but finite, resistance of the multimeter series. However, for each wavelength, the open cell voltage ($\boldsymbol{V_{OC}}$) can be inferred by linearly extrapolating the I/V characteristics to the zero current values. A systematic uncertainty (green error bars of fig.3 right plot) in the extrapolation procedure can be inferred by adopting different data ranges in the extrapolation fit. A linear relationship of open-cell voltages and expected light frequency, $\boldsymbol{\nu}$, has been verified in fig.3 (right-panel). The expected relationship: **$V_{OC} = (\nu - \nu_{min})h/e$** allows the measurement of the Planck constant. Moreover **ν_{min}** , the minimum light frequency exceeding the work function **$W = h\nu_{min}$** can be measured. For this PHYWE-06778 PbS photocell, the expected **$\lambda_{max} = c/\nu_{min}$** = 908 nm value is provided by the cell manufacturer (**ν_{min}** = 330 THz).

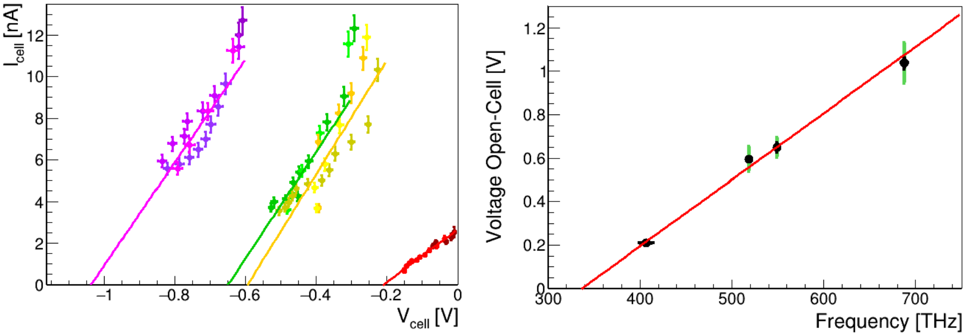

Figure 3. Left panel: Measured I/V characteristics by different student groups for different light wavelengths. The colors are encoding the different wavelengths: 436 nm (magenta points) 546 nm (green points) 578nm (yellow points) and 740nm (red points). Right panel: extrapolated open-cells voltages as a function of the frequency of the light, green error bars represent the systematic uncertainties of the fit.

The measured **ν_{min}** = 336±12 THz, is fully compatible with the expected value for this PbS photocell, however the measured **h** = $3.1 \pm 0.3 \times 10^{-3}$ eV/THz is only marginally compatible with the expected value of Planck constant (4.136×10^{-3} eV/THz = 6.626×10^{-34} Js).

This, typical, ~20% lower **h** value inferred from the measurements of open cell voltages is reported also for the PHYWE-06779 photocell coated with Cs-Sb. From the PHYWE photocell documentation it is correctly suggested that "the errors are partly due to unavoidable photoemission from the anode" and from a simple comparison of the cathode and anode geometric surfaces (see fig.1) a correction factor to the measured currents (and voltages) of the order of ~10% due to the fraction of electrons flowing from anode to cathode should be applied. In particular it is interesting to comment to students that no net current flow is expected in the case of an hypothetical photocell that is perfectly symmetrical among anode and cathode.

3. Conclusions

The proposed approach for the photoelectric experiment, replacing the (expensive) Galvanometer and the tunable voltage source with a series of (low-cost) digital multimeters, normally available in the school laboratories, has been tested. The quantitative measurements of Planck constant and work function agree with the precision expected by this type of experiment using the "standard" (Galvanometer) equipment. The proposed approach allows this important measurement of modern physics also in schools where funds for expensive instrumentations are not available.

Acknowledgments

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