The photoelectric effect – project-based undergraduate teaching and learning optics through a modern physics experiment redesign

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ABSTRACT

The photoelectric effect is a cornerstone textbook experiment in any Modern Physics or Advanced Laboratory course, designed to verify Einstein's theory of the photoelectric effect, with the implicit determination of an experimental value for Planck's constant and the demonstration of the particle nature of light. The standard approach to the experiment is to illuminate the light-sensitive cathode of a vacuum-tube photocell with monochromatic light of known wavelengths; a reversed-voltage is then applied to the photocell and adjusted to bring the photoelectric current to zero. The stopping voltage is then plotted as a function of the inverse wavelength or frequency of the incident light, and Planck's constant is determined from the slope of the graph. Additionally, a value for the work function of the photocathode can be extracted from the intercept. The commercial apparatus for the experiment is available from a number of vendors (PASCO, Leybold) in various forms, degrees of performance and cost. However, designing and assembling a photoelectric effect experiment apparatus can in itself be a valuable experiential project-based undergraduate learning opportunity in Optics involving both fundamental light and optics theory and practical optics and opto-mechanical design aspects. This presentation details a project undertaken in the Applied Physics/Engineering Physics programs at Kettering University involving students in a Modern Physics laboratory course. The first phase of the project, discussed in detail in this paper, was a redesign of an existing photoelectric effect *apparatus* through an undergraduate student thesis, currently in advanced stages of completion. In a second phase of the project we plan to replicate the newly assembled experimental apparatus up to as many as six identical stations and deploy it in our Modern Physics lab course. Typically, more than 50% of the students in this course are engineering majors who would otherwise not get any significant exposure to problems of optics and optical design. We believe that the modular design of the new apparatus together with a carefully redesigned lab activity will allow us to have our students explore major aspects of optics and optoelectronic design while performing this classic Modern Physics experiment.

Keywords: Photoelectric Effect, Planck's constant, experimental apparatus, undergraduate lab

1. INTRODUCTION

1.1 Some fascinating science history and its pedagogical value

A cornerstone discovery at the end of the 19th century and the dawn of the 20th century, the photoelectric effect opened the gateway to quantum physics. It is also a gateway experiment in any current Modern Physics, Optics or Advanced Laboratory course [1, 2, 3]. For lack of time, more often than not a typical lecture or lab on the photoelectric effect will focus on the "exact science" and technical aspect of the effect, and, at best, have an independent reading assignment on the historic context of the discovery. A thorough study of this historic context, however, turns out to not only enliven and humanize the material presented, but to also provide critical technical information to the students. It also provides an extraordinary example of real-life application of the scientific method, as carried out by a number of renowned scientists at one of the most exciting moments in the history of physics. In presenting this historic context, one can engage the students in discussions about the theories and experiments of the time that were either a direct part of the debate, or formed the backdrop against which these debates and discoveries were carried out. The students learn that the scientific discovery process is not a linear process, but rather an iterative process of constructing a puzzle one piece at a time. They learn that well thought theoretical assumptions and carefully designed experiments to verify those assumptions are critical steps in constructing that puzzle. They also learn that seemingly uncorrelated experimental facts can provide critical pieces of the puzzle thus allowing a complete, clear picture to eventually emerge. We find that the scientific "twists and turns" in the discovery of the photoelectric effect are uniquely valuable in bringing these points to life for the students, and including them in the required material for the course bring real value to student learning. For all those reasons, we present some major highlights of that history here.

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The fascinating history of the discovery and eventual theoretical explanation of the photoelectric effect spans some thirty years (1887-1916), and is inextricably intertwined with a number of other great experimental discoveries and theoretical formulations and debates of physics of the time. In particular, the discovery and eventual explanation of the effect was a watershed moment in the debate about the nature of light. As such, this experiment belongs in an Optics lab as much as it does in a Modern Physics lab. The first observation and systematic – though limited, and only experimental – study of the phenomenon belongs to the German physicist Heinrich Rudolf Hertz, in 1886-1887 [4]. This follows Maxwell's theory of electromagnetic radiation, published in 1865, which predicted the existence of electromagnetic waves propagating at the speed of light, and thus concluded that light itself is an electromagnetic wave. In 1886 Hertz became the first experimentalist to successfully verify Maxwell's theory, by generating and detecting electromagnetic waves in a laboratory using an electric apparatus. In subsequent experiments, Hertz was able to measure the velocity and wavelength of the electromagnetic waves he generated and demonstrate their transverse nature. He also studied their reflection and refraction properties and proved they were the same as those of light waves. As a result, he confirmed beyond any doubt that light is an electromagnetic wave.

Interestingly and ironically enough, in proving experimentally that light *is* indeed an electromagnetic wave, as predicted by Maxwell, Hertz also made a "side-effect" discovery, one that would eventually provide the experimental basis for the modern *particle* theory of light to be formulated many years later by Albert Einstein. Indeed, as a transmitter of electromagnetic waves, in his experiments, Hertz used a high voltage induction coil to cause a spark discharge between two pieces of brass separated by a small gap (a spark gap oscillator). As a receiver, to detect the waves generated by the transmitter, he used an open copper wire loop, with a small brass sphere on one end, and the pointed wire at the other end brought in the close vicinity of the brass sphere. In effect, this receiver was a simple half-wave dipole antenna with a micrometer spark gap between the elements, tuned to resonance with the transmitter. The detection of the waves generated by the transmitter was thus made visible by a spark within this micrometer-size gap. What Hertz first noticed in his experiments was that the spark produced by the receiver was stronger (longer) if it was exposed to the light from the transmitter spark. Through a series of thorough experiments Hertz was able to determine that it was the ultraviolet – and not the visible - light of the transmitter spark that was responsible for the effect. However, Hertz made no attempts at explaining the nature of the phenomenon, and, in 1887, he decided, in his own words, to confine himself *"at present to communicating the results obtained, without attempting any theory respecting the manner in which the observed phenomena are brought about*."

Inspired by Hertz' investigation of the matter, in 1888 the German physicist Wilhelm Hallwachs devised a simpler experiment: he would use isolated, negatively-charged, neutral, or positively-charged zinc plates and a gold-leaf electrometer to study the direct effect of ultraviolet light on these objects. His experiments proved that under UV light illumination a negatively charged object loses its charge fast, a neutral object becomes positively charged, and a positively charged object does not leak charge fast. While this did bring more experimental facts clarity to the investigation of the phenomenon, just like Hertz, Hallwachs made no attempt to offer a theoretical explanation of the phenomenon. Nonetheless, this embodiment of the photoelectric effect is known as the Hallwachs effect.

It took another ten years until the experiments performed (independently) by Joseph John Thomson and Philipp von Lenard, aimed at revealing the nature of the so-called cathode-rays, laid also the experimental foundation for a theoretical explanation of the photoelectric effect [5]. Around that time experiments were performed on cathode rays (radiation emitted when a voltage is applied between two metal plates in a glass tube filled with low-pressure gas). In 1897, J.J. Thomson concluded that the deflection of the cathode rays by electrically charged plates and magnets was evidence that the rays consisted of streams of "bodies much smaller than atoms" (later called electrons) which were negatively charged, and calculated their charge-to-mass ratio. Two years later, he determined that illuminating the cathode of a cathode-ray tube with UV light produced the same type of particles - electrons. The 1906 Nobel Prize in Physics was awarded to J.J. Thomson "*in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases*."

In parallel and critical experiments carried out by Phillip von Lenard beginning in 1893, the glass tube was fitted with a thin aluminum window. This made it possible to transmit and study the cathode rays outside the evacuated tube, while preserving the vacuum in the tube. His experiments proved that the cathode rays were not electromagnetic waves. Later on, in a set of carefully designed experiments between 1899 and 1902, Lenard focused on the photoelectric effect and essentially discovered what we know today to be the fundamental features of this effect. Like J.J. Thomson, he showed that when UV light is incident on a metal (the cathode in a cathode-ray tube), electrons are removed from the metal. He showed that those electrons, propagating through the vacuum of the tube, could be deflected by a magnetic field, and accelerated or slowed down by an electric field. They could even be stopped altogether from reaching the anode by an appropriate reversed voltage between cathode and anode, called the *stopping* voltage. Based on these observations, he set to measure the flux (number) and maximum kinetic energy of the electrons emitted by the cathode, in relation to the intensity and wavelength of the incident light. He learned that, at all intensities of light, the effect was practically instantaneous. He learned that the flux of electrons (the electric current) emitted by the cathode depended on the intensity of the incident light, but the maximum kinetic energy of the individual electrons, as measured by the stopping voltage, did not. He also learned that the same kinetic energy did depend, however, on the color (wavelength) of incident light: specifically, the shorter wavelengths produced electrons with higher kinetic energy. His observations in this respect were, however, more qualitative and resulted in energies that were not very reproducible, limited by the quality of the vacuum in his tube which, in time, resulted in partial oxidation of the cathode. Nonetheless, the observations were surprising, and they conflicted with the emerging picture of the explanation of the photoelectric effect based on the electromagnetic theory of light. For all his work, the 1905 Nobel Prize in Physics was awarded to Philipp Eduard Anton von Lenard "*for his work on cathode rays*", but not for the photoelectric effect. Ironically, it was also in 1905 that Albert Einstein, building upon Planck' theory of quanta, formulated his deceptively simple, but revolutionary disruptive theory of the photoelectric effect (discussed in detail in the next section) [6]. The 1921 Nobel Prize in Physics was awarded to Albert Einstein (in 1922) "*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect*," a fact that Lenard could never forgive.

1.2 Einstein's theory of the photoelectric effect

Einstein's explanation of Lenard's experimental results is based on the revolutionary assumption that a light ray or beam is nothing but a stream of "packets" of energy called quanta. This builds on Plank's hypothesis of 1900 that the electromagnetic radiation can only be emitted and absorbed in discrete (integer) multiples of a fundamental quantum of energy given by $\Delta E = h\upsilon$, a hypothesis Planck needed to explain the spectral distribution of energy in the blackbody radiation. This hypothesis also introduced Planck's constant, h. Einstein took that hypothesis one step further and advanced the idea that the electromagnetic radiation field itself is quantized. In Einstein's words, "*the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units*." According to Einstein, each such quantum of energy, which we now call photons, has an energy

$$E = h\upsilon \tag{1}$$

where h is Planck's constant and υ is the frequency of the electromagnetic wave associated with that light ray. Lenard's qualitative experimental results can then be explained in a precise, quantitative way assuming that in the photoelectric effect one such quantum of energy (photon) is absorbed – as a complete unit - by one electron. The most energetic electrons emitted by the cathode are thus predicted to have a kinetic energy

$$KE_{max} = h\upsilon - W \tag{2}$$

where W is a material-dependent constant representing the "work" needed to free the electron from the photocathode. These most energetic photoelectrons can be slowed down if a retarding voltage is applied between anode and cathode. The resultant photocurrent can this be brought to zero for a retarding voltage V_0 called the *stopping voltage*, where

$$eV_0 = KE_{max} \tag{3}$$

With this, Einstein's equation for the photoelectric effect takes the form

$$eV_0 = h\upsilon - W \tag{4}$$

The graphs in Figure 1 summarize the properties predicted by Equation 4. However, the data available in 1905 was not sufficiently accurate to conclusively prove or disprove Einstein's theory. It took another eleven years until, in 1916, Millikan – a firm believer of the wave theory of light - published the results of his series of carefully designed and executed experiments on the photoelectric effect. These experiments, designed to prove that Einstein's particle view of light was wrong, ended up in fact confirming Einstein's prediction. Millikan found a value of $4.128 \times 10^{-15}\ eV \cdot s$ for the slope of the $eV_0\ vs\ \upsilon$ graph using a sodium photocathode (Eqn. 4, Fig. 1c), a number that was in good agreement with the value obtained by Plank from his theory for blackbody radiation [9,10,11]. The Nobel Prize in Physics 1923 was awarded to Robert Andrews Millikan "*for his work on the elementary charge of electricity and on the photoelectric effect*."

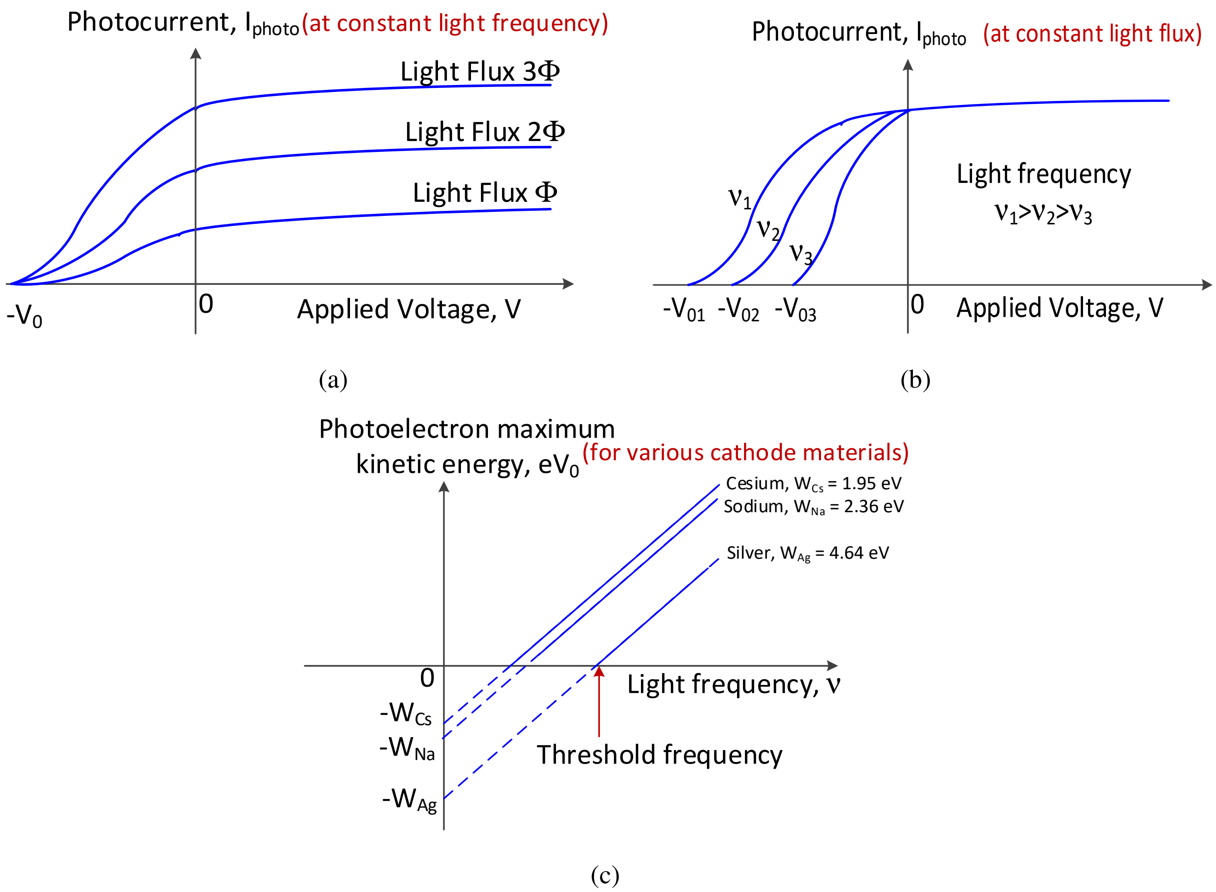


Figure 1. A graphical summary of the properties of the photoelectric effect, as predicted by Einstein's 1905 equation for the effect (Eqn. 4) and verified experimentally (in a qualitative way) by Lenard between 1900 and 1902

2. PROJECT METHODOLOGY

2.1 Common experimental apparatus

This project began with a literature review by the student of both the history and theory of the photoelectric effect, and of the commercially and non-commercially available versions of the experimental apparatus. While many colleges and universities have a commercial version of the apparatus in use for their Modern Physics, Advanced Lab or Optics Lab, the search also revealed a number of creative home-assembled (in university labs) forms of the apparatus. We found this search in itself to be of great pedagogical value that allowed us to explore, analyze, compare and contrast the claimed performance, complexity of the apparatus, cost, accessibility and flexibility vis-à-vis our intended mode of use. As stated earlier, a commercial experimental apparatus for the study of the photoelectric effect is available from a number of vendors. Figure 2 shows the apparatus available from PASCO [7] for around $3,700. The apparatus consists of a self-enclosed low-pressure mercury light source and the associated power supply, a self-enclosed proprietary vacuum-tube photocell unit outfitted with a filter wheel concentric with an aperture wheel, a power supply that provides the voltage (variable from positive to negative) to be applied between the photocathode and the anode of the photocell, and a current amplifier and meter for the measurement of the very small photocurrent generated in the photocell under the effect of the incident light. The low-pressure mercury lamp emits discrete, sharp spectral lines of 365, 405, 436, 546, and 577 nm respectively. Each one of them can be selected, in turns, as the excitation wavelength to illuminate the photocathode by rotating the filter wheel and placing the appropriate narrow band-pass filter in front of the photocell. In addition, the incident light intensity can be set to one of three possible levels by selecting an appropriate aperture in front of the band-pass filters. The current amplifier can measure photocurrents in the range of 10^{-8} to 10^{-13} A (manually selectable range). The proprietary, nickel-anode-ring vacuum photocell has a stated dark current of 20×10^{-13} A.

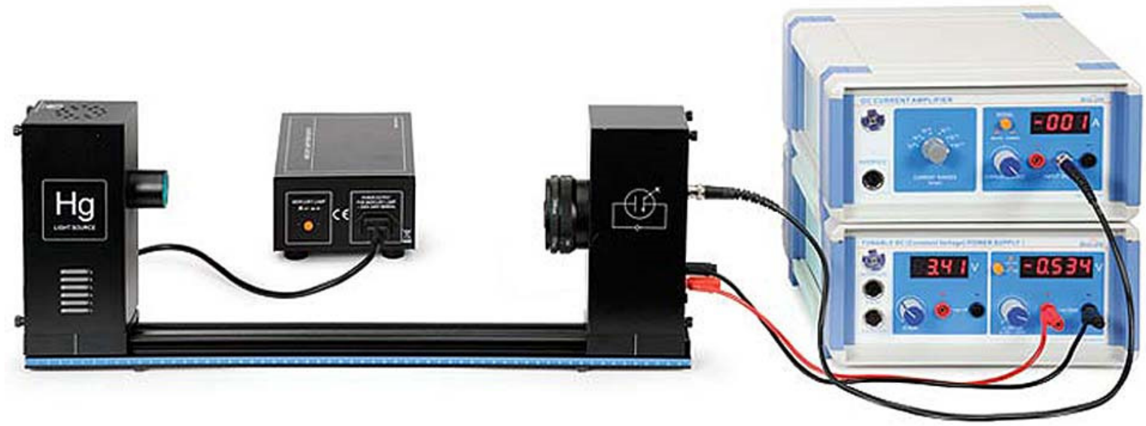


Figure 2. Photoelectric effect commercial experimental apparatus from PASCO [7]

There is no question that the PASCO setup is a high-quality (if not very cheap) commercial setup for the study of the photoelectric effect. It allows the students to collect in a time-effective way all the data and produce all the curves discussed in section 1.2, thus verifying all of von Lenard's findings about the effect. It further allows them to verify Einstein's theory of the effect and calculate Plank's constant to within (according to PASCO) 5% or better of the commonly accepted value. These are all virtues of this apparatus one should not minimize. What is does *not* allow on a routine basis, or even reasonably easy, is for the students to experiment with the intricacies of the setup itself to gain a better understanding of the factors that affect their experimental measurements. At $549 replacement cost for the photocell inside the enclosure, even a look at it may not be feasible or desirable on a regular basis. Our goal is to have a redesigned experimental apparatus for the photoelectric effect that produces accurate results for Plank's constant while at the same time allowing students to "tinker" - at least to some extent - with the apparatus, analyze its optical design (possibly even assembling it from submodules or even individual components) and figure out the effects on their experimental results.

2.2 Current photoelectric effect apparatus at Kettering University

At Kettering University we have been using for a long time (for historic reasons) a photoelectric effect bench-top setup that uses a vacuum-tube photocell (RCA/Cetron/GE 1P39 or 929) followed by an operational (trans-impedance) amplifier and associated power supplies and meters. The cell is illuminated by the expanded beam of one of four helium-neon lasers (543.5 nm green, 594 nm yellow, 612 nm orange and 632.8 nm red). Using lasers rather than filters ensures a narrow spectral width of the illuminating beam. At the same time, it makes the benchtop setup very expensive to replace or replicate, susceptible to misalignment of the lasers, and altogether rather bulky. It also requires the experiment to be performed in a dark (dim) room to minimize stray room light into the photocell, as there are no laser-line band-pass filters in front of the photocell window. Another drawback is the relatively narrow spectral range covered by the four lasers (543.5 to 632.8 nm) which results in somewhat larger errors in determining Plank's constant.

2.3 Redesigning the photoelectric effect apparatus

Due to the age of the lasers – which are also the costliest components in our setup - during the past year we have been exploring options for a more compact benchtop setup that could be replicated in a cost-effective manner for up to six stations and which would allow the experiment to be performed with room lights on. This challenge presented itself also as an opportunity to consider the pedagogical value of the setup being actually designed (to some extent, with significant input from the faculty supervisor), assembled and tested by a student. It must be mentioned that at Kettering University, each undergraduate student (of any major) must work on a Culminating Undergraduate Experience (CUE) project which results in the completion of an undergraduate thesis as a graduation requirement. Consequently, a senior Applied Physics major (Brendan Book) was selected for the project to work under the guidance of Dr. Corneliu Rablau (thesis supervisor), Dr. Uma Ramabadran (thesis committee member) and Robert Cunningham, MS (Lab Supervisor). The practicality of the problem required that the high-level design (i.e. selection of the basic approach and major components of the apparatus) be led by the supervising faculty and staff, rather by the student himself. This was fundamentally dictated by cost considerations, and still had the student involved at every step of the process. The various possible high-level designs were analyzed with the student and discussed in relation with the known parameters and constraints of the project. The main considerations were the targeted initial cost per station, the number of stations to be assembled, the cost and availability of replaceable components (such as vacuum tube photocell, low pressure mercury lamps, broader bandpass or narrow band interference filters) and the desired technical and pedagogical outcomes of the redesign. All these address very well student outcome 2 (SO2), one of the six student outcomes required of the ABET accredited Applied Physics program at Kettering, which is "*an ability to formulate or design a system, process, procedure or program to meet desired needs*." Once the overall layout of the new apparatus were decided upon through this team work (next section), the major building blocks were acquired and the student was tasked to work mostly independently, with minimal guidance, to test individually the components of both our current setup and of the intended redesigned apparatus, and have the new components assembled into a prototype system and perform an actual photoelectric effect experiment on the new system.

One of the major considerations in a photoelectric effect apparatus is the selection of the light source and wavelength selector (if necessary). The two work in tandem to produce the monochromatic light of selectable wavelengths required to perform the experiment. The use of already monochromatic light sources (like HeNe lasers, laser diodes, laser pointers) is a possibility, one already employed at Kettering so far. While lasers can simplify the apparatus (in general) by eliminating the need for a wavelength selector, they also can pose other problems that need to be considered, particularly if used as free-space unenclosed beams. In particular, safety issue related to laser power are paramount when working with students. The availability of several wavelengths at appropriate power levels and spanning a wavelength range wide enough and compatible with the spectral response curve of the vacuum photocell is also a consideration. The overall size of the setup and optical alignment issues are also factors, particularly if using HeNe lasers of various sizes and form factors. These are all very practical aspects of actual optical design, and ones that the student involved in this current project had to consider in performing the photoelectric experiment with our current setup and analyzing the results obtained. As already known to the faculty and staff advisers, while working and producing satisfactory results, our current setup is not optimal, a conclusion reached by the student himself. A second possibility is the use of a multi-wavelengths or broadband light source, in conjunction with an appropriate wavelength selector. Quite often a low pressure mercury light source is used, like in the PASCO apparatus discussed earlier. A set of bandpass filters are then used, one at a time, to select one of the several narrow spectral lines present in the lamp emission. The demand on the performance of the filters is not too stringent since the filters are used only to select one of the otherwise rather narrow and well separated line emissions of the mercury lamp. The filter itself does not determine the spectral width of the light illuminating the photocathode. Another filter-based approach is the use a higher power broadband light source (a quartz-tungsten-halogen lamp or a high pressure mercury or xenon arc lamp) in conjunction with narrow band pass (interference) filters. This is the approach taken, for example, by the Leybold commercial photoelectric effect apparatus [8], which uses a broadband high-pressure mercury lamp and a set of interference filters. The performance of the filters becomes critical in this case (and the cost for them goes up dramatically), as the individual filter now determines the spectral width of the illuminating light. Even better, while using either a low pressure mercury lamp or a broadband light source a small monochromator can be used as a wavelength selector, though this can add up significantly to cost, in general. This approach, which provides the maximum possible flexibility in selecting virtually any number of monochromatic lines to illuminate the photocathode was eventually employed in our redesign, as discussed in the next section.

3. TECHNICAL AND PEDAGOCICAL ASPECTS OF THE PROJECT

3.1 Technical aspects

Figure 3 presents a picture of the assembled redesigned apparatus. It consists of a low pressure mercury lamp, a small compact monochromator outfitted with a vacuum phototube attachment, and the associated electronics for applying and measuring the voltage on the phototube and for measuring the photocurrent produced by the phototube. Assembled for roughly half the cost of a PASCO commercial apparatus, this setup has a number of both functional and pedagogical advantages. One major advantage is its modular construction that involves more standard, broad-use components, as opposed to proprietary PASCO components that are dedicated solely for the photoelectric effect experiment. In particular, the measurement of the photocurrent is done using the new Keysight (Agilent) 34461A 6½ digit multimeter (Agilent 34401A replacement). This is a top-of-the-line, high performance, multi-use, industry workhorse test and measurement instrument that can be acquired for a didactic cost of $900, equal to the cost of the dedicated current amplifier in the PASCO setup. This was a very pragmatic pedagogical decision on the part of our team, to allow our students to gain experience in working with an instrument widely used by both industry and universities. The versatility of this instrument is a critical advantage as it can be used in a number of other Modern Physics and Optics experiments, unlike the dedicated PASCO amplifier. The electrical circuit diagram of our apparatus is presented in Figure 4.

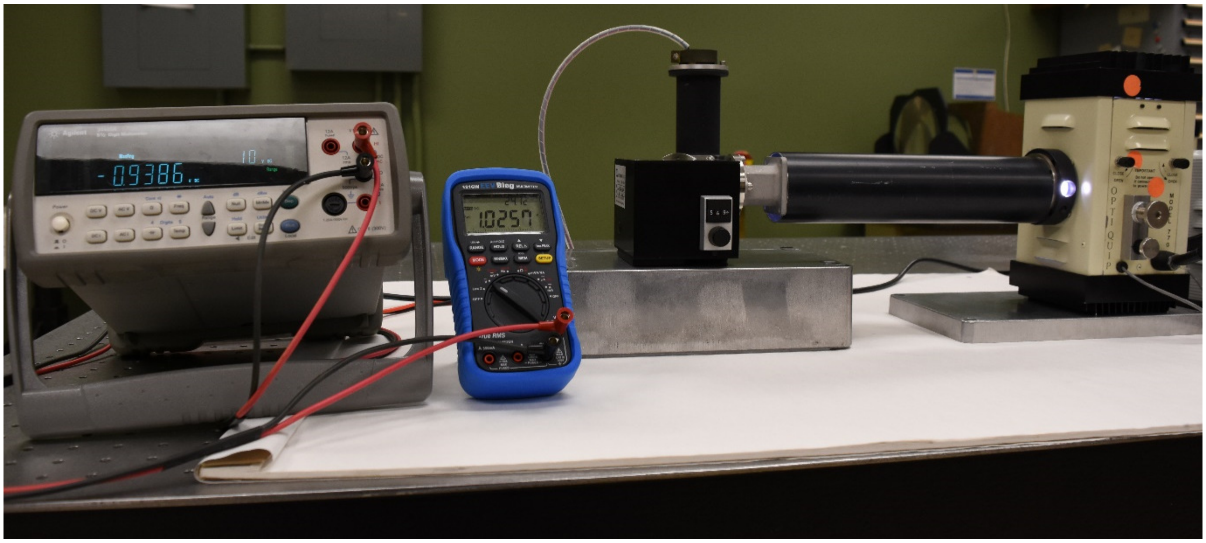


Figure 3. Photoelectric effect experimental apparatus assembled through this project (I will replace picture with pour own)

To minimize noise, a battery stack is used to apply a reversible-polarity voltage to the phototube (as opposed to an AC-line-powered DC power supply). The voltage can be controlled using a 10-turn potentiometer between -3 V and +18 V, thus allowing the collection of complete current-voltage characteristics as presented in Section 1.2 Figure 1. The -3 V negative limit is more than enough, considering the work function of the photocathode used. The photocurrent, spanning the range of roughly 10^{-13} to 10^{-8} A (0.1 pA to 10 nA) is measured by measuring the voltage drop on the 100 KΩ resistor. This boils down to measuring voltages as low as 0.010 μV, which are well within the range of the Keysight 34461A multimeter. The collection of the entire I-V curve from positive voltages to negative voltages all the way to zero current and – as experiment demonstrates - down actually into very small *negative* currents is essential for a precise determination of the stopping voltage.

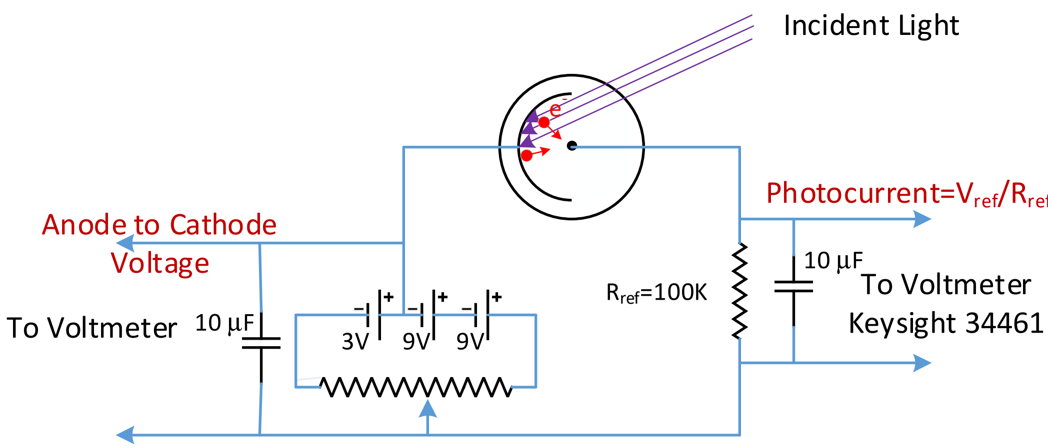
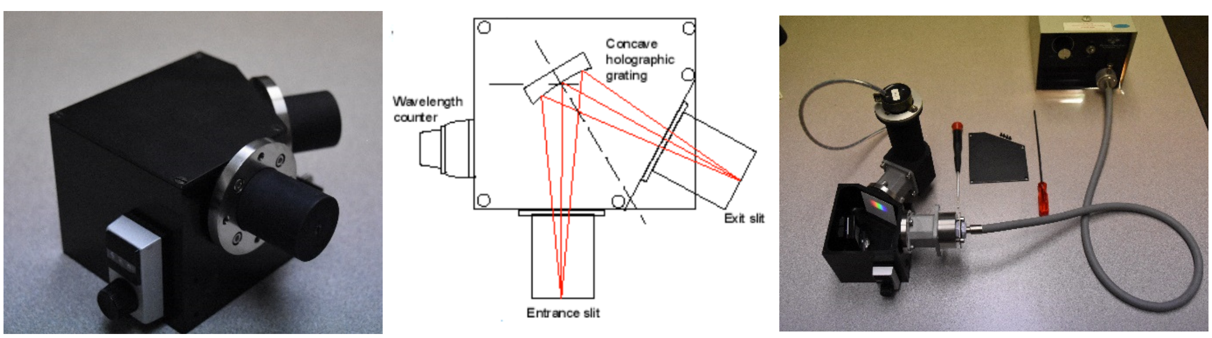


Figure 4. Circuit diagram of the photoelectric effect apparatus

The central, essential component of our apparatus is the monochromator outfitted with a vacuum phototube attachment (Figure 5). In a serendipitous type of occurrence, while exploring the options for our experimental apparatus redesign, our team was able to acquire (at a small fraction of their actual cost) a number of Horiba H10-61 (Jobin-Yvon H-1061) monochromators that were used as internal components in retired semiconductor industry equipment. These Original Equipment Manufacturer (OEM) monochromators are integrated and used in various industrial applications for wavelength verification or bandpass selection – in perfect alignment with their intended use as wavelength selector in our photoelectric effect apparatus. To quote from the Horiba H-1061 spec sheet, "*the H10-61 monochromator series are simply the most trouble-free monochromators in the world, because they contain just one optical element, an aberration-corrected holographic grating. They are compact, robust, and easy to setup*." Horiba is not exaggerating! With a compact size of only about $10\ cm \times 9\ cm \times 8cm$ (excluding the flanges that accommodate the entrance and exit slit), the monochromator has a very simple and robust construction and is manually driven with a direct wavelength reading in nm graduated to 0.2 nm. Internally, it is outfitted with only a concave grating (1200 lines/mm) which eliminates the need for internal mirrors and ensures a large enough light throughput even for a low intensity input light source. The spectral range is 200 to 800 nm. The band pass (with 500 μm slits) is about 1 nm, more than suitable for our application. The simple construction allows for very easy access to view the internal components and for relatively easy calibration of the monochromator. Equally exciting, the entrance and exit slit flanges provide for easy and secure mechanical and optical integration of the monochromator with the other components of the apparatus. In particular, the vacuum phototube is mounted directly into a cylindrical housing that attaches securely to the exit slit flange, providing for light-tight integration that allows the experiment to be performed free of room light interference. Figure 5c presents the monochromator with the top cover removed and outfitted with a phototube. A white light fiber optics source is used at the input, and the diffracted spectrum can be seen projected on a white card placed internally in front of the exit slit. It also allows for a modular construction of the apparatus which can be easily assembled or disassembled – even down to individual components - and stored on the shelf. This modular construction also allows the use of the monochromator in other experiments. In particular, we plan to integrate these monochromators in our lab activity focused on studying the hydrogen spectrum for the determination of the Rydberg constant. Currently, we use a traditional didactic spectroscope that employs a diffraction grating on a goniometer stage and direct observation of the spectral lines through a telescope. The H-1061 monochromator would augment, rather than replace, this current setup. Using the monochromator outfitted with the phototube, we will be able to detect more lines of the Balmer series of hydrogen, potentially down to the short-wavelength series limit of 364.6 nm (656.3, 486.1, 434.0, 410.2, 397.0 and down to 364.6 nm), all well within the spectral response of the phototube.



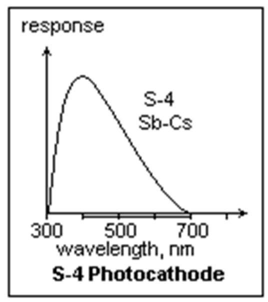
(a) (b) (c)

Figure 5. The Horiba H10-61 compact monochromator used in the redesigned photoelectric effect apparatus (a), the light path through the monochromator (b), and the monochromator outfitted with the phototube mounted on the exit slit (c)

The component at the heart of a photoelectric effect itself is obviously the vacuum phototube. In this current age of microprocessors and integrated circuits, the choice of vacuum phototubes readily available as stand-alone components for the photoelectric effect is rather limited, and eventually for our project boiled down to one of two options. The first considered was the Hamamatsu R-414 phototube, a current production 10-mm diameter phototube with a front end window and a ring anode, available for around $180 per piece. The second option was the older RCA/Cetron/GE 1P39 (or its equivalent 929), a phototube with a Sb-Cs cathode having a so-called S4 response curve. It is also the tube used in our old photoelectric apparatus. The response of the tube peaks at 400 nm and extends between 300 nm and 700 nm. Although no longer in production, these phototubes are still available either as used or New Old Stock (NOS) components for prices ranging from $25 to $100 per piece. The 1P39 (929) is a side illumination, straight wire anode at the center of a half-cylinder photocathode and is some three times larger than the Hamamatsu R-414. The tube fits into an octal vacuum-tube base, fully compatible with the mechanical housing that mounts onto the exit-slit mounting flange on the monochromator. A very important feature is the fact that the mechanical housing of the phototube can be mounted either vertically or horizontally on the H-1061monochromator. This allows the student to asses which of the two configurations results in less light falling onto the wire anode, thus minimizing the number of electrons that can be (potentially) emitted by the anode rather than the cathode. All these characteristics made the 1P39 the phototube of choice for our new experimental apparatus.

Finally, the light source to be used in our new apparatus is an OPTiQuip Nobska 100 W low pressure mercury lamp. Designed to be used as an excitation light source for fluorescence microscopy, it is compact and provides appropriate power levels for our experiment. In particular, the 365, 405, 436, 546, and 577 nm lines of the mercury lamp are matched very well to the S4 responsivity curve of the 1P39 phototube. As an alternative, the use of the monochromator as wavelength selector also offers the flexibility of using a broadband light source, instead of the discreet-line mercury light source. This can extend the range of wavelengths that can be use beyond the 577 nm line of the mercury lamp, but not more than approximately 650 nm due to the rapid decay of the tube responsivity curve. In either case, the output of the light source can be delivered to the input slit either through line-of-sight free space as in our current apparatus (although enclosed by a connecting tube), or via an optical fiber. This will however require UV-transmitting fibers at least down to 350 nm.

(a)



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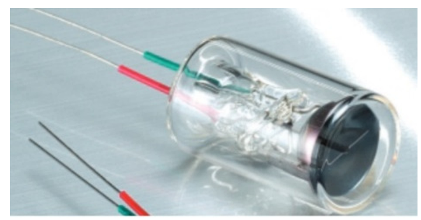

(c)

Figure 6. The side-window RCA/GE/Cetron 1P39 (929) vacuum phototube (a), its so-called S4 spectral response curve (b), and the front-end-window R-414 Hamamatsu phototube (c)

3.2 Student learning aspects of the project

Researching, testing and assembling these components in a complete system provided plenty of opportunities for the student to learn optics by practicing optics. The student had to perform such activities as:

- Reviewing the construction of two of the most widely used commercial setups for the photoelectric effect, namely the PASCO apparatus and the Leybold apparatus [7,8] The manuals provided by vendors contain sufficient technical detail to make this a very enriching student learning experience, both with respect to the photoelectric effect itself and with respect to the design approach, which is fundamentally optical in nature.
- Completing a literature search on a number of components and assemblies (light sources, monochromators, phototubes, bandpass filters, low current amplifiers, digital multimeters, etc.) and analyze their technical specifications and costs in relation to the requirements of our intended use of the apparatus
- Manually (mechanically) calibrating the H-1061 monochromator using a reference wavelength (632.8 nm HeNe laser line) and test that calibration using at least a second laser wavelength (543.5 nm). This, by its nature, exposes the student to the optics of diffraction gratings and the operation of a diffraction-grating monochromator
- Recording the spectrum of the low pressure mercury lamp. A small fiber-coupled Ocean Optics Red Tide 650 spectrometer controlled by Vernier's LoggerPro software was used for this purpose. This provides another exposure to optical spectroscopy, this time specifically focused on the automatic, computer controlled acquisition of a spectrum.
- Verify the output of the H-1061monochromator, manually tuned to the individual mercury lamp wavelengths, using the Red Tide spectrometer. This verifies both the calibration of the monochromator, but also the linewidth of the mercury lines at the input of the phototube.
- Investigate a number of vacuum phototubes as potential candidates for the photoelectric effect apparatus. This involved studying both vacuum and gas-filled phototubes, and analyzing their spectral response in relation to the available wavelengths produced by the mercury lamp.

- Investigate the possibility of using a broadband light source (quartz-tungsten-halogen) instead of the low pressure mercury lamp. This is made possible by the use of the monochromator as a wavelength selector, and involves verifying the monocromaticity/spectral width of the output of the H-1061 monochromator when using a broad band light source as input. The monochromator has input and exit slits of 500 μm fixed width.
- Test the performance of the system vis-a-vis the orientation of the 1P39 phototube with respect to the orientation of the exit slit of the monochromator, for reasons discussed earlier.
- Perform a literature search on the analysis and processing of raw data produced by an experiment investigating the photoelectric effect. While the theory outlined in Section 1.2 for the extraction of Planck's constant from the slope of the $eV_0\ vs\ \upsilon$ graph is straight forward, extracting the precise value of the stopping voltage V_0 from the current-voltage characteristic of the phototube is actually a more complex procedure than the simple (standard textbook) procedure of measuring the voltage at which the photocurrent becomes zero. The photocurrent actually crosses into very small negative numbers, due to electrons being emitted from the anode under incident light.

4. PRELIMINARY RESULTS

With the student in final stages of collecting and analyzing a first set of data with this new apparatus, we present here some preliminary results of the actual measurements. While important for the outcome of this project, and even more so for the photoelectric effect experiment to be performed in the lab with a full class, the quality of the graphs produced by the student and the value for Plank's constant extracted from these measurements becomes only one of a number of the measures of the student learning through this project. It is apparent that a more precise method of extracting the actual stopping voltage than the simple "voltage at zero current" is needed to improve on the value of h.

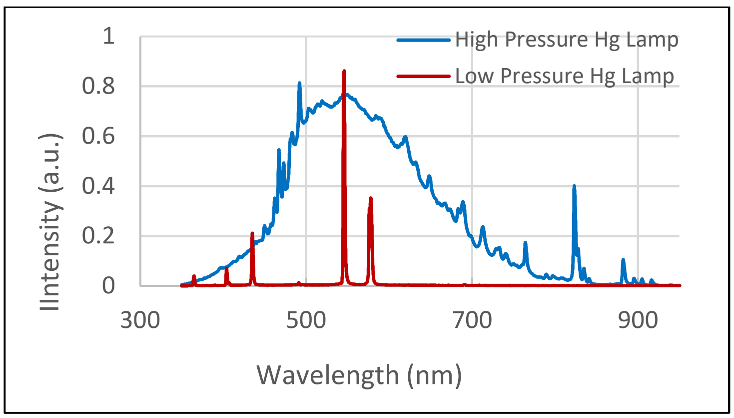

Figure 7. The spectra of a high-pressure mercury lamp and a low-pressure mercury lamp investigated as potential light sources for the redesigned photoelectric effect apparatus (to be used with a monochromator wavelength selector)

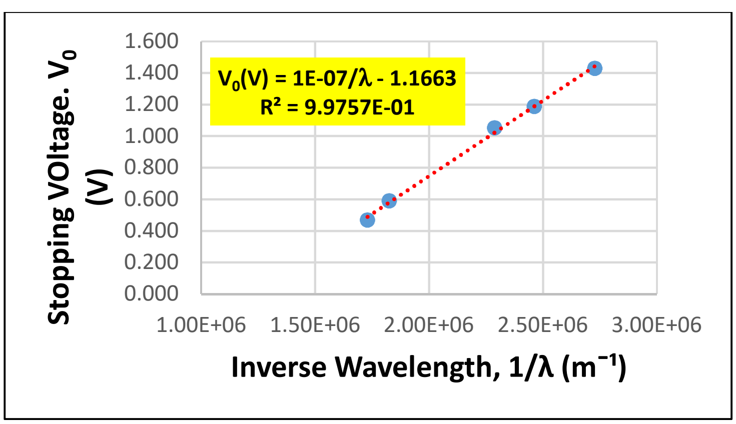

Figure 8. Stopping voltage as a function of inverse wavelength for the 1P39 photoelectric tube. The resulting value for Planck's constant is $5.34 \times 10^{-34}\, J \cdot s$, which is 18% off from accepted value. The work function of the cathode is 1.166 eV

5. CONCLUSIONS AND FUTURE WORK

We have presented, in its context, an undergraduate student project of designing and assembling an experimental apparatus for the study of the photoelectric effect. While the experiment itself is part of a Modern Physics course, the activities involved in the design and assembly of the apparatus were very much of an optics design, assembly and testing in nature. Such activities provided the student with both theoretical knowledge and practical skills of optics, optoelectronics and optical spectroscopy. With the modular design of the apparatus simple and robust enough, we plan to deploy it in a redesigned photoelectric effect lab activity for physics and engineering majors. On the theoretical part, the redesigned activity will emphasize both the historic context of the discovery of the effect and the watershed significance of its theoretical explanation by Einstein in the debate regarding the nature of light. On the practical activity side, we intend to use the modular design of the apparatus to expose the students to elements of optics design (e.g. the internal design of the monochromator and its advantages), optical spectroscopy (discreet light sources, broadband light sources, filters) and optoelectronics (vacuum phototubes as light detectors, spectral response of a detector, aging of the detector, etc.).

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