We describe in detail the construction of a detector circuit used to investigate the photoelectric effect. The design of the circuit is based on a PASCO Scientific ‘$h/e$ Apparatus’ used in modern physics demonstrations. Some preliminary results are presented and estimates for the work function and $h/e$ are obtained. We also discuss the problem of damping out the intensity dependence of the circuit response, and provide various other suggestions for improving the experiment.

I. INTRODUCTION

The history of the experimental observation of the photoelectric effect is hard to detail precisely; the photoemission of electrons from metallic cathodes had been observed several times, but the first identification of these mysterious ‘cathode rays’ as electrons was J.J. Thomson’s celebrated experiment in 1897 [1]. Other noteworthy contributors to the study of cathode rays include Hertz [2] and Lenard [3]. The first satisfactory theoretical description of the effect was given by Einstein, in one of his famous 1905 papers[4].

In this paper, we describe the construction of a simple apparatus for investigating the photoelectric effect. The design of our detector circuit is based on a PASCO Scientific demonstration set-up used in many introductory modern physics courses. Due to manufacturing constraints, our apparatus has significantly more problems related to residual intensity dependence in the circuit; however, in spite of this, it is possible to make a measurement of the work function of the photocathode material and of the ratio of Planck’s constant to the electron charge ($h/e$). We find that there is roughly a 10% error in our experiment, and suggest ways of improving the accuracy and stability of the measurement.

This paper is divided into five sections as follows: we first provide a brief description of the theoretical understanding of the photoelectric effect and outline some of the key predictions that we hoped to test. Next, the working and construction of the phototube and associated electronics are explained. We then present some of our preliminary results, and go on to discuss the sources of inaccuracy in our measurement leaving a detailed discussion of the intensity dependence to Appendix A. We finish with a discussion of our conclusions and provide some suggestions for the future of the experiment.
II. EINSTEIN’S THEORY OF THE PHOTOELECTRIC EFFECT

In his seminal theoretical paper, Einstein [4] provided an elegant explanation of the photoelectric effect based on the corpuscular (‘particle’) theory of light quanta proposed by Planck. We consider the collision of a light quantum of frequency $\nu$ with an electron bound to a metallic surface. All the details of the binding of the electron to the surface are assumed to be contained in a quantity known as the work function, $\Phi_0$, which represents the minimum energy needed to cause emission of a photoelectron from the cathode surface. Using Planck’s theory, the energy of the photon is $h\nu$, and using conservation of energy, we have that

$$h\nu = \Phi_0 + T$$  \hspace{1cm} (1)

where $T$ is the electron kinetic energy. In practice, the electron kinetic energy is measured by employing a ‘stopping potential’: this slows electrons as they approach the anode, and effectively reduces the current seen by an ammeter placed at the anode. The current drops to zero when the energy drop across the stopping potential exactly equals the electron kinetic energy, i.e. when $T = eV$. Therefore, we find that

$$h\nu = \Phi_0 + eV$$  \hspace{1cm} (2)

Using this, we see that the stopping potential depends on the incident frequency as

$$V = \frac{h}{e} \nu - \Phi_0^{(eV)}$$  \hspace{1cm} (3)

where $\Phi_0^{(eV)} = \frac{\Phi_0}{e}$ is the work function in electronvolts.

Thus, plotting the stopping potential against the incident frequency allows us to compute the work function and the value of $h/e$ from the $y$-intercept and the slope of the straight line that the theory predicts. (Figure 1)

Notice that the theory also predicts the following interesting facts:

(i) The stopping potential (and hence the electron kinetic energy) depends only on the frequency of the incident photon and not on the intensity.

(ii) There is a minimum threshold frequency of $\Phi_0/h$ required before a photoelectron may be emitted.

(iii) In an ideal situation, the intensity of light affects only the photocurrent measured at a given frequency when the stopping potential is set to zero; intuitively, this is because increasing the intensity increases the incident photon flux to the photocathode, which increases the number of electrons emitted.
III. THE APPARATUS

The conventional apparatus for studying the photoelectric effect is rather cumbersome: it involves a vacuum tube with a photocathode and a light source whose frequency could be controlled (usually a helium lamp as it has a wide range of spectral lines). The stopping potential is measured by varying the anode voltage until the current drops to zero.

The method we used is based on that used in the PASCO Scientific h/e apparatus [5]. This is based on a rather simple idea: a phototube exposed to light works as a variable light-sensitive capacitor if one grounds the cathode plate. The emission of electrons leads to a potential difference between cathode and anode; the photocurrent continuously charges the capacitor until the potential difference across the capacitor exactly equals the stopping potential, at which point the charging stops. The stable final voltage across the ‘capacitor’ (phototube) is thus the stopping potential of the photoelectrons. One can see intuitively that if this were an ideal circuit the intensity of incident light would only affect the time required for the reading to stabilize (since it would vary the charging photocurrent) and not the value of the stable reading itself.

We use an AD549 operational-amplifier with an ultrahigh input impedance and unity gain to allow this voltage to be measured by a conventional multimeter. Details of the working of the operational amplifier can be found, for example, in [6] or [7]; information specific to the AD549 may be found in [8]. We have two phototubes: one is a 1P39 tube that was removed from the PASCO apparatus, and the other is a Hamamatsu 935 tube. The 935 tube is highly sensitive in the ultraviolet region and as a result does not give reliable results with our current set-up. Therefore, our preliminary results were obtained using the 1P39 phototube. The 935 tube can potentially be used in the future, but care must be taken to protect it from stray UV sources, particularly since mercury lamps are known to emit in the UV. A grounding switch is provided to reset the phototube when the measurement has been made since the tube can retain the potential difference for a long period of time unless one actually shorts the circuit. A full circuit schematic is provided in Figure 2.

We reconstructed the circuit using components identical to those used by PASCO; instead of etching the circuit we used conventional wire connectors on a breadboard. This may explain the increased fluctuations seen in our measurements due to possible inductances or capacitances produced inadvertently through our circuit design. Also, we noticed a significant intensity dependence that we discuss in Appendix A, which may be due to stray impedances in the circuit and non-ideality in our components.

A monochrometer was used to obtain light of a single specific frequency by using a fine diffraction grating
and an adjustable system of lenses and mirrors that permits the selection of a single line from a source that has a multitude of spectral lines. The monochromator was not used for obtaining our preliminary results, as the intensity dependence leads to a very weak signal when one isolates a single spectral line of relatively low intensity compared to the broadened spectrum from the coarser grating provided by PASCO.

The light sources used were a standard mercury-vapor lamp (also from PASCO Scientific) with a diffraction grating used to separate spectral lines, and a sodium-vapor lamp to obtain an additional line. The sodium doublet cannot be resolved by the PASCO grating, and therefore we average over the two frequencies to obtain an ‘effective’ frequency that is used in our analysis. Appropriate color filters were fitted over the slit so that only light of a given frequency is transmitted to the tube.

Since we have residual intensity dependence, it is extremely important to operate under identical conditions for each frequency, as this will diminish to some extent its effects. We took care to use the grating even for the sodium lamp (even though it is of no practical utility in resolving the lines) so that the same attenuation and beam size -and hence intensity - were obtained at the slit of our measuring apparatus as when the mercury lamp was used.

**IV. PRELIMINARY RESULTS**

We did a preliminary experiment using the PASCO 1P39 tube in order to test the circuit and determine to what extent our intensity dependence affected our results. We decided not to use the monochromator for reasons stated in section III, and performed the experiment using the PASCO grating to separate our spectral lines. The measurements were made in low-light conditions, with the only light source being the lamp.

We do three separate calculations with our data:
(i) we use the theoretical values of $h$ and $e$ to compute the work function;
(ii) we use the estimated work function provided by PASCO to compute $h/e$
(iii) we fit a straight line to our data points, and read off the value of $h/e$ and the work function from the slope and $y$-intercept

(i) and (ii) are mainly done as consistency checks; (iii) provides the ‘real’ experimental values for both quantities. Our linear fit gives us a value of $h/e$ of $3.867 \times 10^{-15}$ JsC$^{-1}$, which is an error of about 6.5% from the theoretical value of $4.136 \times 10^{-15}$ JsC$^{-1}$. The work function estimated in this way turns out to be 1.282 eV; there is no definite value provided by PASCO for the work function of their tube, but a rough
estimate is 1.45 eV; our value then has an error of 11.6% relative to this one.

Our plot does not have error bars because the major source of error is from the intensity dependence, which remains a serious challenge to quantify. Although our work in low-light conditions reduces some of the effects of intensity dependence, we cannot eliminate the effects of relative intensity differences between the various spectral lines. This leads to a ‘rotation effect’ on our linear fit, since each frequency has its stopping potential shifted from its ‘correct’ value by differing amounts thereby affecting the slope. In essence, a universal dependence on the intensity would affect only the work-function (y-intercept) but not the value of $h/e$ (the slope), but an intensity dependence that varied by frequency could affect the slope as well.

We discuss the possible impact of our intensity dependence on the measurement in Appendix A.

V. CONCLUSIONS AND OUTLOOK

Although we do not have a fully working photoelectric effect experiment at this point in time - due to the intensity dependence that we have been unable to fully remove - we believe that it can be improved to the point where the experimental error is significantly reduced from its current level. Our measured values of $h/e$ and the work function are fairly close to what we expect them to be; a little work will improve our results greatly. We have the following estimates:

(i) $h/e = 3.867 \times 10^{-15}$ JsC$^{-1}$ (approx. 6.5% error)
(ii) $\Phi_0 = 1.282$ eV (approx. 11.6% error from theoretical estimate of 1.45 eV.)

There are two categories of suggestions that we would like to make for the future of this experiment. The first consists of ideas of where errors are produced in our current experiment and what we believe needs to be done before our experiment reaches the level of a reliable apparatus for taking data. The second category is a set of ideas for interesting experiments that could be performed once the apparatus reaches this stage.

A. Apparatus Development

• The Circuit Board: The intensity dependence in the circuit is a worrisome problem that has no clear resolution. One suggestion is to perhaps attempt to construct a circuit board along the lines of the one constructed by PASCO, which would minimize any stray resistances/inductances that could give us a current dependence. Such a current dependence could manifest itself as an intensity
dependence, since the current in the circuit depends on the intensity. Exactly to what extent this
dependence can be removed is still very much an open question. Improving the circuit will also
increase the stability of the measurement, since any stray electric or magnetic fields could couple
to current loops and produce voltage drops that cause fluctuations in the output voltage. Trying
another op-amp might also be a good idea, in case of manufacturing defects in the present device.

- **The Monochrometer:** As of now, we do not actually use the monochrometer to isolate frequencies.
Using the coarser grating produces more error, since there is far more potential for lines to overlap
than in the monochrometer, making the measurement suspect as it may be produced by a pair of
frequencies rather than a single line.

- **The Geometry:** After constructing the box in which our circuit and tube are housed, we realized
that the placement of the slit is not as in the PASCO set-up. It is perhaps possible that there are
certain gains in positioning with the slit perpendicular to the axial plane rather than parallel to it
as we currently have. However, if the circuit can be improved sufficiently, any lingering geometric
effects should be irrelevant, since the geometry only affects the intensity of the incident light, and not
its frequency. Reducing stray light is also an important improvement that can be made; we noticed
significant differences when stray light sources were blocked.

**B. Future Experiments**

- **Computerization and Study of the Light-Sensitive Capacitance:** The measurements are
currently made using a conventional multimeter. Using LABVIEW and a Data Acquisition System
would allow us to measure not only the stable stopping voltage, but also to study the time to
stabilization and how the voltage stabilizes as it approaches the stopping potential. Since we have
what is in essence an RC circuit, and the dependence on incident photons is in the capacitive part
of the circuit, we realize that we could also characterize the intensity and frequency dependence of
the variable capacitance of the phototube.

- **The 935 Tube:** Currently, the experiment uses a 1P39 tube from the PASCO apparatus; our own
tube, a Hamamatsu 935, is not in use due to the UV sensitivity mentioned. It would be very satisfying
to have some reliable data using the 935 tube as well. In fact, the design of our experiment makes it
very modular, allowing any tube with a 5-pin octal base to be used in the detector, and so testing
various different tubes and characterizing their spectral response is an interesting side project.

- **Polarization Dependence of the Photoelectric Effect:** It would be interesting to study the dependence of photoemission on polarization: which parameters, the stopping potential or the stabilization time, (if either) are affected by the polarization? What is the dependence, and how is it explained by the theory?

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**Acknowledgements**

The authors would like to thank Nicholas Bigelow, Sergey Korjenevski, Ryan Camacho and Chris Haimberger for several helpful ideas and insightful discussions, and John Gresty and Colin Kingsley for help with machining. S.A.P. would like to thank Ryan De Rosa for his advice and input. Parts of our circuit were obtained from the Electrical Engineering Machine Shop at no charge, for which we thank the supervisors.

**Appendix A: Intensity Dependence: Causes, Consequences and Cures**

We believe that we can explain the intensity dependence using a simple model. Let us model the incident light as a frequency-dependent charging emf $E$ for our phototube ‘capacitor’, with some resistance $R$ that can be used to model the intensity ($R$ is some function of frequency and various other parameters such as the geometry) - this will be the ‘Thevenin Equivalent’ of our light source. Our problem is to determine the steady-state potential difference across the capacitor. In the ideal case (Figure 4(a)), where $R$ is the only resistance in the circuit, this is a straightforward problem: we have an $RC$ circuit, and in the long run the potential difference across the capacitive element is just the source voltage, i.e. $V(t \rightarrow \infty) = E$. Suppose that our circuit is nonideal, and that there is some kind of ‘shunt resistance’ in parallel with our capacitor (Figure 4(b)). Then, one sees that the steady-state capacitor potential difference changes to include our ‘intensity dependent’ component $R$: $V(t \rightarrow \infty) = \frac{E}{1+R/p}$. In this way, the measured voltage can acquire a frequency dependence. It is possible to show that similar effects can also be produced by stray capacitances or inductances. Therefore, even minor defects in the circuit design may leave the door open for frequency dependence of the output; this is not a frequency dependence of the photoelectric effect - *that* would be rather surprising, and not a little unnerving - but of our measurement process. An intensity dependence leads indirectly to a dependence on the geometry of the device, as well as to the sort of ‘rotation’ of our
$V - \nu$ plot that was discussed in section IV. Our results then become rather more uncertain, and significant errors are introduced into our measurement. It is hoped that some of these effects may be eliminated by the suggestions for redesigning the circuit outlined in Section V.

[8] Analog Devices Operating Instructions for AD549 Operational Amplifier
   (http://www.analog.com/UploadedFiles/Data_Sheets/274408122AD549_e.pdf)
FIG. 1: The Photoelectric Effect. Plot of stopping potential against frequency of incident light. The $x$-intercept is the threshold frequency, while the $y$-intercept is the work function in electronvolts. The slope of the curve gives the value of $h/e$. Image from http://www.physics.northwestern.edu/new335/PDF/planck.pdf.
FIG. 2: Schematic of Photoelectric Effect Detector Circuit. Image from [5].
FIG. 3: Preliminary Results. Plot shows stopping potential against frequency of incident light (cf. Fig. 1.) A linear fit to the date provides estimates of $h/e$ and the stopping potential:

$h/e = 3.867 \times 10^{-15}$ JsC$^{-1}$

$\Phi_0 = 1.282$ eV
FIG. 4: Explaining the Intensity Dependence:

a) In the ideal case, the steady-state voltage depends only on the frequency, since the Thevenin emf, $E$ only depends on frequency.

b) In the case where there is a stray shunt resistance $r$, the steady state-voltage has a dependence on the Thevenin resistance $R$, which brings in the intensity-dependence.