Lab Report B-II: Photoelectric Effect

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The photoelectric effect demonstrates the properties of photons that puzzled classical physicists. In this lab, we confirm these non-classical properties by observing the dependence of stopping potential and charge time on the angular frequency and intensity of incident light. We find that electrons are only ejected when the angular frequency ω exceeds the threshold frequency $\omega_0 = (1.497 \pm 0.006) \times 10^{15}$ rad/s, and that ω_0 is independent of light intensity. We also conclude that the number of electrons ejected increases with increasing intensity. In observing these properties, we found the reduced Planck's constant to be $\hbar = (1.165 \pm 0.002) \times 10^{-34}$ Js, which does not agree with the nominal value of $\hbar = 1.055 \times 10^{-34}$ Js. This is likely because our uncertainty was too small, since our linear fit only accounted for uncertainty in our measurements of the stopping potential.

I. INTRODUCTION

Classical physics was unable to accurately predict and describe the photoelectric effect, even after its discovery in an 1887 experiment by Heinrich Hertz. The effect occurs when light collides with a metal plate, causing electrons to eject from the plate in the form of photoelectrons. The violations of classical expectations observed by Hertz are as follows: for incident light, a material-dependent angular frequency ω_0, rather than intensity, serves as a threshold needed to eject electrons; once this threshold is reached, the number of ejected electrons depends only on the intensity of incident light; due to its relation to the threshold, the maximum kinetic energy of the photoelectrons increases with incident light frequency ω, while staying independent of light intensity; electrons are emitted near-instantly from the surface [1]. The goal of this lab is to confirm all of these observations and support the quantized particle nature of light.

II. THEORETICAL BACKGROUND

A. Energy Transfer

In this experiment, photons collided with electrons on a piece of metal, transferring energy to the electrons. The electrons were bound weakly to the metal, and thus were ejected from the metal when enough energy was transferred into them. Due to the inelasticity of these collisions, kinetic energy is K_{max}, the maximum kinetic energy the electron can have. Relating K_{max} to potential energy PE and total energy E, we see that

$$K_{max} = E - PE. \tag{1}$$

Prior to ejection, these electrons sat in a potential energy well. This well relates to the threshold frequency mentioned in the introduction. The energy gained by the electrons must be enough to escape the potential well, thus the energy of the incident photons must be greater than the energy needed to remove the electron from the well. This is known as the work function Φ.

Albert Einstein postulated that each photon has an energy described by the equation

$$E_\gamma = \hbar\omega, \tag{2}$$

where $\hbar = h/2\pi$ and h is Planck's constant. Plugging Eq. 2 into Eq. 1, and substituting the potential energy PE for the work function Φ gives

$$K_{max} = \hbar\omega - \Phi. \tag{3}$$

It is important to note that Φ is equal to $\hbar\omega_0$, with ω_0 being the aforementioned threshold frequency. Thinking about this equation intuitively, kinetic energy will only be positive (meaning the electron will be ejected) when the energy transferred to the electron is greater than the energy required to break free of the metal (Φ). Considering

$$KE = \hbar\omega - \hbar\omega_0 = \hbar(\omega - \omega_0), \tag{4}$$

we see that the frequency of incident light must be greater than the threshold frequency for electrons to be ejected.

B. Measurement

Understanding how the ejection mechanism works, we can move on to data collection. We want to gather the emitted electrons on a collector plate to measure them, but they do not necessarily move towards our plate; instead, they go in various directions after ejection, and some do not have sufficient kinetic energy to reach the plate. To fix this, we can apply a voltage that creates an electric potential, causing electrons to move uniformly towards the collector plate. This creates a current on the plate, which is proportional to the number of electrons flowing. By manipulating the voltage applied, and, in turn, the electric potential, we can find the minimum voltage necessary to eject electrons and thus produce a current. This is known as V_0, the stopping potential.

Knowing this, we can make a substitution in Equation 3, since the electric potential of a photoelectron is equal to its maximum kinetic energy due to conservation of energy. This yields

$$K_{max} = eV_0, \tag{5}$$

where e is the charge of an electron. This expression can be plugged into Eq. 3 to give us

$$eV_0 = \hbar\omega - \Phi. \tag{6}$$

We can also determine charge time using careful analysis mentioned in Methods.

It is important to note that in order to measure stopping potential and charge time with respect to wavelength, we need to determine the wavelengths involved. The diffraction grating in the goniometer setup split the incoming light into bands, as mentioned in Methods, so we can measure the angles of the resulting bands to calculate wavelength. The equation

$$\lambda = \frac{sin(\theta)}{n \times N} \tag{7}$$

was used for this, with n being the diffraction order of the band, N being the line density, and θ being the angle measurement of the band. Knowing wavelength, one can then calculate the angular frequency, ω.

III. METHODS

A. Procedure

We performed four experiments: one measuring stopping potential versus intensity, one measuring charge time versus intensity, one measuring stopping potential versus wavelength, and one measuring charge time versus wavelength. In our analysis of the data, we found that observing wavelength versus charge time was unnecessary to the goal of the lab, and thus omitted that experiment.

A goniometer spectrometer apparatus was used in the setup, and consisted of a Mercury Vapor Lamp, a lens with 610 lines/mm diffraction grating, and a Pasco Scientific model AP-9368 h/e photodetector apparatus with two 9V batteries installed. The photodetector apparatus was attached to a swiveling arm such that it could be rotated to align with bands of light, and the associated angle could then be measured to within 1° (Fig. 1). Using Eq. 7, the wavelength of light in the band can be calculated, and frequency can be found after.

To measure stopping potential, we used the photodetector apparatus to record V_0 values in LoggerPro. For the trials testing wavelength dependence, bands of light scattered at various angles around the goniometer were evaluated by the apparatus, and the angle recorded. The "push to zero" button was pressed prior to measurement

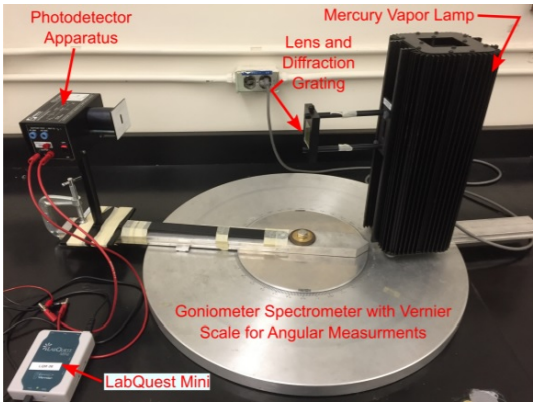

FIG. 1: Diagram of goniometer-spectrometer setup, with gimbal arm and attached photodetector.

in order to get an accurate reading. For the trials testing intensity dependence, a filter allowing for 100%, 80%, 60%, 40%, and 20% of the light to pass through was placed in front of the detector apparatus for each respective measurement.

Measuring charge time was a matter of finding a constant point on the curve V_0 followed. After pressing the "push to zero" button, V_0 dipped to 0 and immediately began to asymptotically approach its proper value. Due to the nature of this curve, we chose to stop the timer when the fluctuation in the V_0 reading decreased to ± 0.001 away from the final V_0 reading. Evaluating the relation of charge time to wavelength and intensity followed the same procedure used to find the relation of stopping potential to wavelength and intensity.

B. Uncertainty Analysis

Because V_0 was measured by observing an asymptote in LoggerPro, it was difficult to pinpoint an exact value to record. Because we waited until the value of V fluctuated by only 0.001 V, our uncertainty in V_0 was ± 0.001 V. We assume this probability distribution to be uniform.

Charge time had two sources of uncertainty. First, we took three measurements for each intensity, and so the variance was simply the standard deviation σ squared. Second, as mentioned previously, there was no single moment at which we had to stop the time. Therefore, we included uncertainty that varied from measurement to measurement based on how much time we felt we had missed the stopping potential by. Because this is a vague criteria, the average uncertainty was ± 4 s. We took this uncertainty to be a triangle distribution, since we were fairly confident that the actual value of charge time was close to the recorded value. Nonetheless, these variances combined to yield relatively large error bars on the plot of charge time (Fig. 4).

Uncertainty in angular frequency was propagated through quadrature. This uncertainty does not factor

into our weighted linear fit.

Intensity was not measured; rather, we used a filter with set intensities. As such, we did not have uncertainty in intensity.

IV. RESULTS

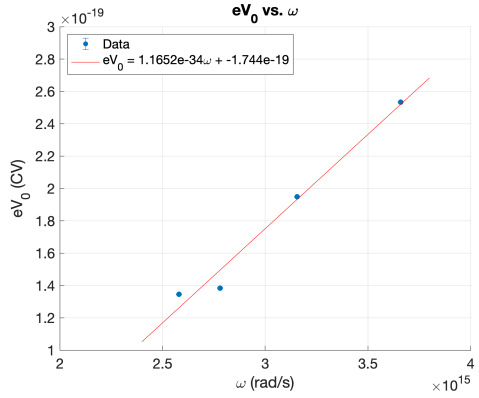

FIG. 2: This plot shows that stopping potential V_0 increases with angular frequency ω. It has a slope of $\hbar = (1.165 \pm 1.9478) \times 10^{-34}$. Although error bars are included, they are too small to be visible on the plot.

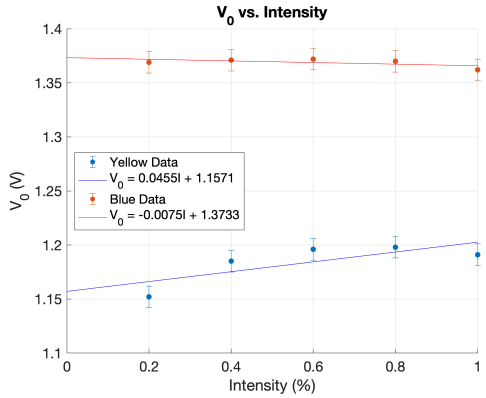

FIG. 3: The top line shows the stopping potential V_0 vs. intensity for the blue emission line, and has a slope of $m = -0.008 \pm 0.002$. The bottom line shows the same relationship for the yellow emission line, with a slope of $m = 0.046 \pm 0.002$.

We fit the data in Fig. 2 to Eq. 6, such that the slope was $\hbar = (1.165 \pm 0.002) \times 10^{-34}$ Js and the y-intercept was $-\Phi = (-1.744 \pm 0.006) \times 10^{-19}$ J. Extrapolating an intercept on the x-axis from the graph, we find that $V_0 = 0$ when $\omega = (1.497 \pm 0.006) \times 10^{15}$ rad/s.

V. DISCUSSION AND CONCLUSIONS

We confirmed the non-classical nature of the photoelectric effect. Fig. 2 shows that as angular frequency ω increases, the stopping potential V_0 also increases. With the relationship between K_{max} and V_0 shown in Eq. 5, we know that the maximum kinetic energy must also increase with angular frequency. From the same figure, $\hbar = (1.165 \pm 0.002) \times 10^{-34}$ Js. This does not agree with the nominal value of $\hbar = 1.055 \times 10^{-34}$ Js, but it is on the same order of magnitude, indicating that our data is accurate but the range of uncertainty is likely too narrow. Similarly, the value of the work function, $\Phi = (1.744 \pm 0.006) \times 10^{-19}$ J, does not agree with the accepted work function of aluminum, $\Phi = 6.5369 \times 10^{-19}$J [2]. Our uncertainties in both $\hbar$ and Φ come from a weighted linear fit taking into account the uncertainty in our measurement of the stopping potential V_0, but not the uncertainty in angular frequency. A more thorough uncertainty analysis including variance in both variables may have yielded larger uncertainties that allow our data to agree with the accepted values.

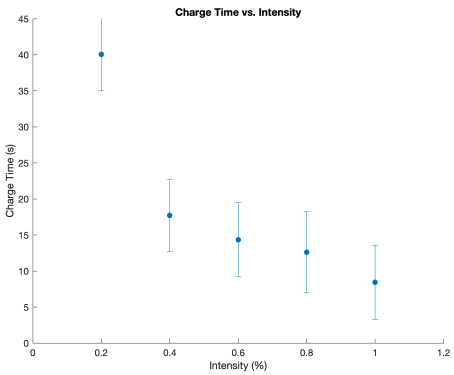

FIG. 4: As intensity increases, charge time decreases.

Using the extrapolated intercept of Fig. 2, we find any frequency lower than $\omega_0 = (1.497 \pm 0.006) \times 10^{15}$ would not cause electrons to eject, since kinetic energy would be less than or equal to 0. This frequency is therefore the threshold frequency. The fact that no electrons are emitted until the frequency reaches ω_0 demonstrates that particles of light are quantized. This is because each electron requires a specific amount of energy before it can be ejected.

Fig. 3 shows that stopping potential V_0 is independent of intensity, since the plots of both the yellow and blue emission lines are nearly constant. Thus, the maximum kinetic energy is also independent of intensity. These plots also show that higher angular frequencies yield higher stopping potentials, since the stopping potential of the blue light is always higher than that of the yellow light.

From Fig. 4, we find that the charging time decreases with increasing intensity. Although the error bars are large, this relationship is still clear. This suggests that as intensity increases, more electrons are ejected.

In performing this lab, we only had access to a yellow filter. This means that any other emission lines ob-

served were really the product of many different angular frequencies combining together. For this reason, we excluded data from Fig. 2 collected at the red emission line, since we could not isolate the red wavelength. To mitigate this effect for the other plots, we chose to use the yellow emission line as our incident light for any experiments measuring intensity while keeping angular frequency constant.

VI. ACKNOWLEDGMENTS

The experiment was performed by C.S. and N.M., and C.S. recorded the data. N.M. wrote the Abstract, Introduction, Theoretical Background, and Methods sections. C.S. wrote the Results and Discussion and Conclusions sections, and also performed data analysis. Data was fit using the LinFit MatLab function provided by Ben Levy.

[1] Lab B-II Manual
https://sakai.unc.edu/access/content/group/41081125-b301-4ad9-8173-970601749ad6/Lab\%20Manuals/Lab\%20B-II\%3A\%20The\%20Photoelectric\%20Effect/Lab\%20B-II\%20Photoelectric\%20Effect.pdf

[2] Work Functions for Photoelectric Effect
http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/photoelec.html