

Planck's Constant

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Phys. 2033: Quantum Lab

1 Purpose

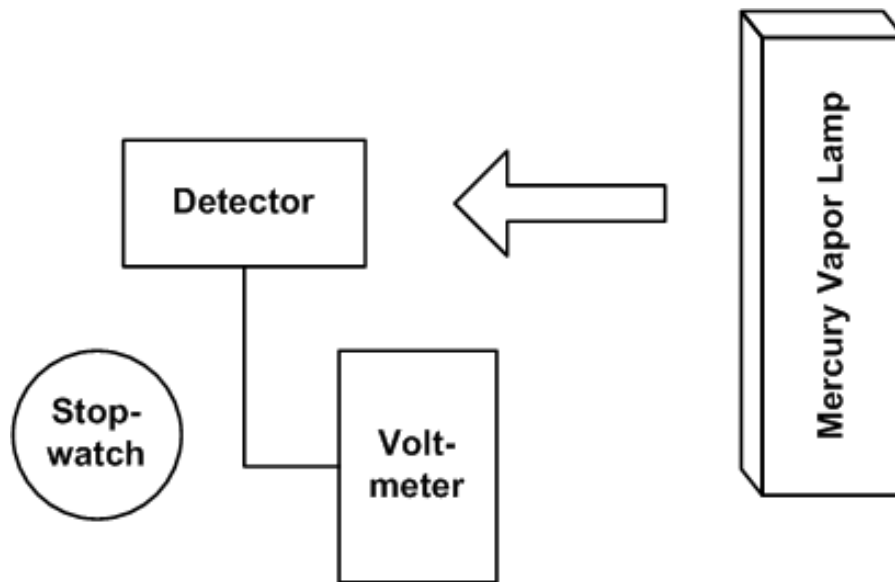
The purpose of this lab is to observe the photoelectric effect, and specifically how kinetic energy is defined using stopping potential. Using a grating lens, we investigated the properties of a Mercury Vapor light source. We examined each of the five component colors separated by the lens by measuring the stopping potential and charge time of each color.

2 Methodology

Using the equipment described below we collected two sets of data. Each data set is explained in detail in the *Collected Data* section. Our overall method involved splitting the source light into its components, and then measuring the stopping potential and charge time of each under different conditions.

2.1 Equipment Used

For this lab, we used an h/e Apparatus connected to a voltmeter. As shown below, the source light is projected through a grating lens. By moving the detector at a constant radius from the lens, we could examine specific color components of various orders.



The Apparatus was powered by two 9V batteries, and was fitted with various filters to aid data collection. We also used a stopwatch to measure the charging time.

2.2 Physics Demonstrated

When thinking about light, classical physics says that more light implies more energy. However, Einstein and others predicted that light followed a quantum pattern, and so it has a single energy regardless of intensity.

In our experiment, we point light at a metal plate inside a detector. Electrons are emitted from the plate when photons hit it. We can then measure those electrons as the stopping voltage V . When thinking of the light, it needs an initial energy W_O to bump the electrons out of the metal. Any extra energy left over is simply kinetic energy.

$$E = hf = E_K + W_O \quad (1)$$

We also know how kinetic energy is related to the stopping voltage, and can combine that to solve for V .

$$hf = Ve + W_O \quad (2)$$

$$V = (h/e)f + (W_O/e) \quad (3)$$

That last equation looks just like the slope equation $y = mx + a$, which we will use to our advantage later in the lab.

3 Collected Data

Below we list all data collected as we progressed through the lab.

Transmission (%)	Stopping Potential (V)	Charge Time (s)
100	0.898	16.1
80	0.896	9
60	0.892	6.7
40	0.887	9.6
20	0.871	13.5
100	0.773	15.1
80	0.772	9.1
60	0.769	6.6
40	0.765	10.4
20	0.753	14.4

Table 1: Stopping potential and measured charge time for the green and yellow bands of the spectrum. Green appears first followed by yellow after the horizontal bar. Gradient filter was used to change light transmission amounts.

Color	Wavelength (nm)	Frequency ($10^{14}Hz$)	Stopping Potential (V)
Yellow	578	5.19	0.776
Green	546	5.49	0.902
Blue	436	6.88	1.547
Violet	405	7.41	1.751
Ultraviolet	365	8.20	2.042
Yellow	578	5.19	0.648
Green	546	5.49	0.667
Blue	436	6.88	1.468
Violet	405	7.41	1.645
Ultraviolet	365	8.20	1.965

Table 2: Measurements of stopping potential for given light band. The first two orders of magnitude are listed, separated by a horizontal line.

4 Analysis and Results

4.1 Light as Waves or Particles

After setting up the device, we measured the stopping voltage and charge time of each of the five component colors from the light source. This collected raw data is shown in *Tab. 1* above. We used a gradient filter to make multiple measurements over several transmission levels.

4.1.1 Describe the effect that passing different amounts of the same colored light through the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.

As shown in *Fig. 1*, when transmission level was decreased, we clearly see how the stopping potential slightly decreases. The classical model of light predicts that the stopping potential will strongly drop off as intensity decreases. Although we observed a decrease, it is not the magnitude predicted by classical theory.

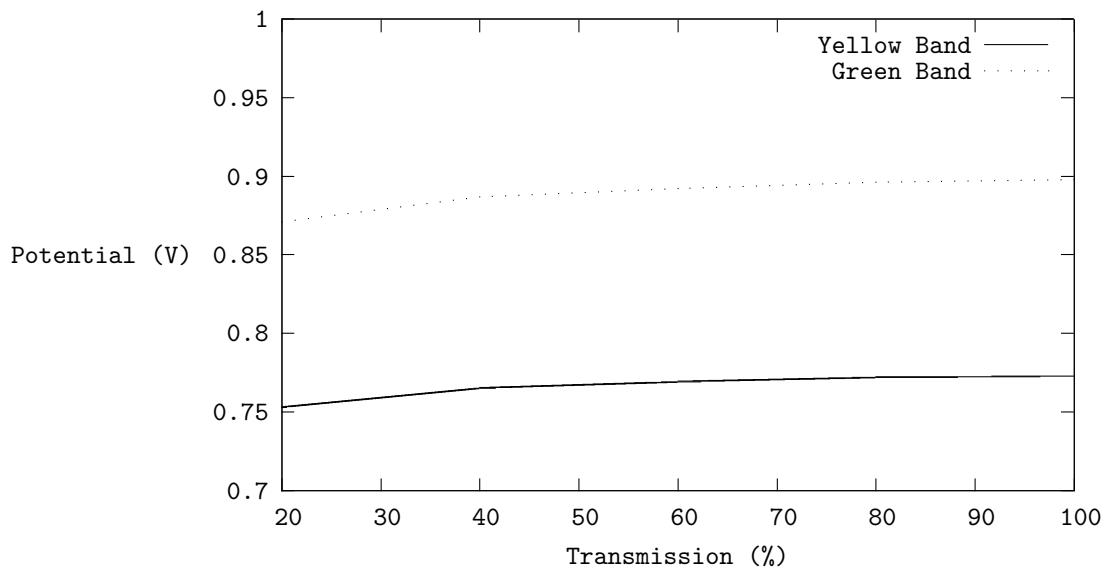


Figure 1: Plot of stopping potential for yellow and green light as transmission rates are varied.

As shown in *Fig. 2*, the charging time we measured follows a parabolic shape; decreasing to its lowest point at 60% transmission while maintaining roughly equal maximums at both 100% and 20% transmission. However, the quantum theory of light predicts that charging time should increase steadily as we decrease intensity.

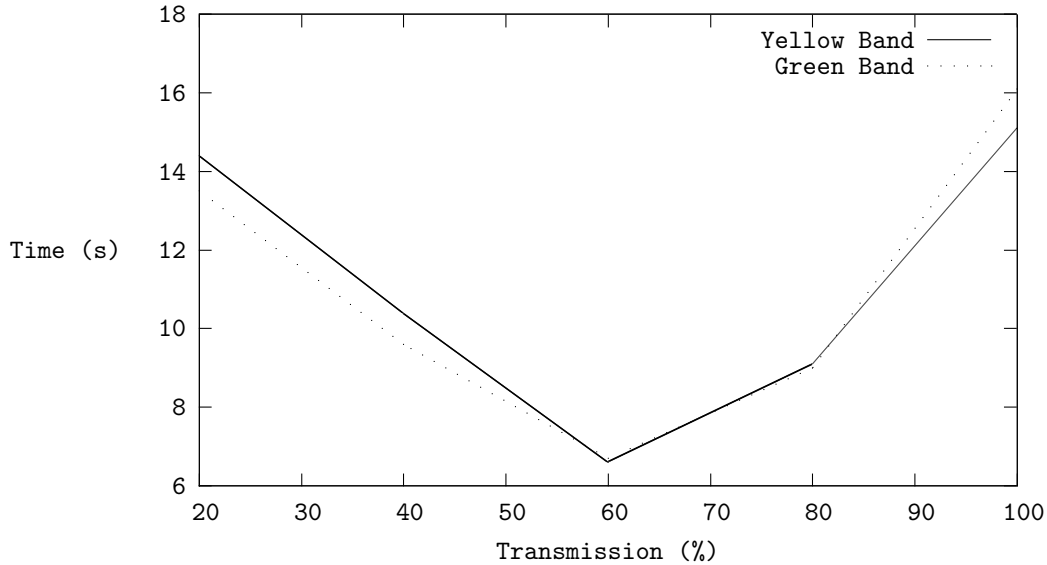


Figure 2: Plot of charging time for yellow and green light as transmission rates are varied.

In our experiment, we notice very high readings for the 100% transmission reading in both cases. We are reminded that these timing calculations were performed using a stopwatch and manual readings from a voltmeter, and are subject to error.

4.1.2 Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.

As we examined successively lower wavelengths of light, the stopping potential increased. We also know that stopping potential is related to kinetic energy using the quantum equation:

$$E_K = Ve \quad (4)$$

As shown in *Fig. 2*, we see that kinetic energy E_K is directly related to the stopping potential V . Thus, the lower wavelengths had increased kinetic energy. Our data shows that this quantum relationship holds.

4.1.3 Defend whether this experiment supports a wave or a quantum model of light based on your lab results.

Our measurements of stopping potential and charging time both follow the quantum model of light. They clearly do not follow the results predicted by classical theory. We discussed the differences expected between the two models in the sections above.

4.1.4 Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.

From our earlier definition of the stopping voltage, we know that it relies on a work constant of the detector W_O . While stopping potential does not depend on intensity, the work constant **does** dependant on the light intensity. The slight drops are due to the change in the work constant W_O .

4.2 Relationship between Energy, Wavelength, and Frequency

4.2.1 Determine the wavelength and frequency of each spectral line. Plot a graph of the stopping potential versus frequency.

From our equation earlier, we know how stopping potential is related to frequency through Planck's constant h . We could solve for f and calculate using the accepted value of h along with our observed value for V . However, we know that the Mercury Vapor lamp gives off specific wavelengths of light, as outlined in *Handbook of Chemistry and Physics, 46th ed.* and quoted by our apparatus manual.

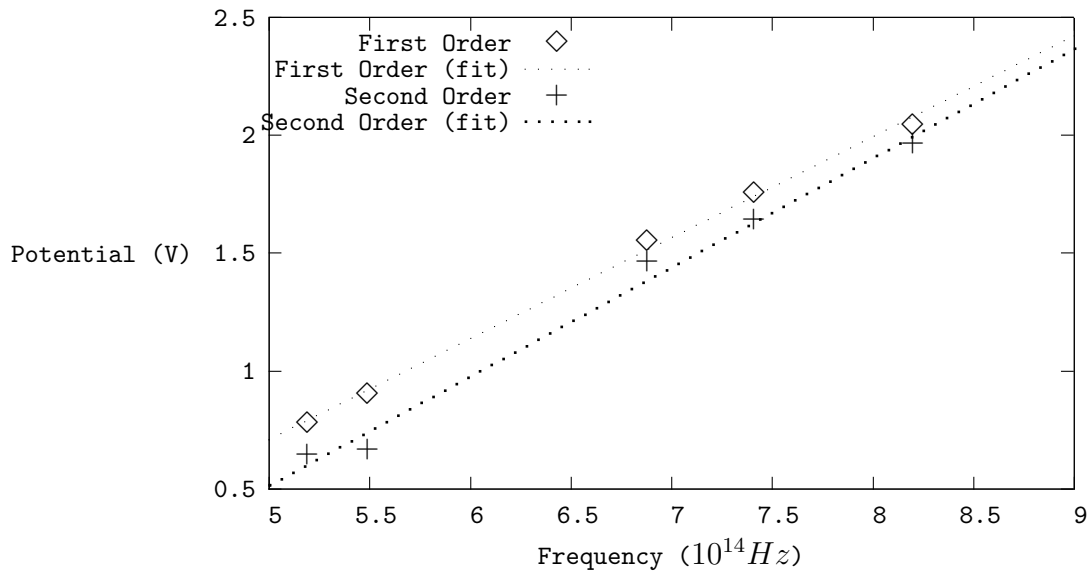


Figure 3: Plot of stopping potential for the given frequencies measured. The first two orders of five different colors were measured.

We choose to use those accepted values to better calculate our h and W_O later. These accepted values of f and λ are shown above in *Tab. 2* along with the recorded stopping potential for each band of light.

4.2.2 Determine the slope and y -intercept. Interpret the results in terms of the h/e ratio and the W_O/e ratio. Calculate h and W_O .

Using a linear fit for the data collected above, we calculated the slope and y -intercept of each of the two orders. Results are listed in *Tab. 3* below. The actual linear fit lines defined by these values have been superimposed over the data in *Fig. 3*.

Order	Slope (m)	y -intercept (a)
First	0.428	-1.43
Second	0.463	-1.8

Table 3: Calculated slopes and y -intercepts for the first and second orders. Original data was provided by *Tab. 2* above.

Looking at the linear fit slope we can derive a value for h , and looking at the y -intercept we can derive a value for W_O . In the equations below, we keep the first and second orders separate. As noted in the table above, m refers to the slope and a to the intercept. We also remember that the m used above is reduced by a factor of 10^{-14} due to our units of frequency.

$$m = \frac{h}{e} \quad (5)$$

$$h_1 = me = (0.428 \times 10^{-14})(1.602 \times 10^{-19}C) = \boxed{6.857 \times 10^{-34} J \cdot s} \quad (6)$$

$$h_2 = (0.463 \times 10^{-14})(1.602 \times 10^{-19}C) = \boxed{7.417 \times 10^{-34} J \cdot s} \quad (7)$$

$$a = \frac{W_O}{e} \quad (8)$$

$$W_{O1} = ae = (1.43)(1.602 \times 10^{-19}C) = \boxed{2.291 \times 10^{-19} J} \quad (9)$$

$$W_{O2} = (1.8)(1.602 \times 10^{-19}C) = \boxed{2.884 \times 10^{-19} J} \quad (10)$$

For Planck's constant h , the accepted value is $6.626 \times 10^{-39} J \cdot s$. Looking at our calculated values above, we find an error of $\pm 0.231 \times 10^{-34}$ for h_1 and $\pm 0.791 \times 10^{-34}$ for h_2 . Below are our final averaged values across both orders.

$$h = \boxed{(7.137 \pm 0.511) \times 10^{-34} J \cdot s} \quad (11)$$

$$W_O = \boxed{2.588 \times 10^{-19} J} \quad (12)$$

5 Error Analysis

In this lab, we worked with a voltmeter accurate to $\pm 0.00005V$. We chose to measure voltage only to three significant figures. As such, the error inherent in the voltmeter is extremely low, and we chose to neglect it.

When measuring the charge time, we used a stopwatch accurate to $\pm 0.1s$. However, the stopwatch was operated by a human, and was subject to human error. When any time data appeared to fall outside of a trend, we repeated that part of the experiment to verify the value. Values reported in the table above are averages of all measurements taken.

When looking at our calculated values for Plank's constant h , they are 3.49% from the accepted value for the first order, and 11.94% for the second order. A broad conclusion is that more error is introduced when measuring orders further from the first order.

6 Conclusion

In this lab we observed the photoelectric effect. We examined how stopping potential and charging time operate for a Mercury Vapor light source. We thought carefully about the results predicted by both the classical and quantum theories of light. Along with the data we presented above, we argue that light is governed by the quantum theory and disprove that it follows classical theory.

Using measurements from two orders of diffraction, we estimated h to be $(7.137 \pm 0.511) \times 10^{-34} J \cdot s$, which is 7.71% from the accepted value for h . We also calculated the W_O of our detector to be $2.588 \times 10^{-19} J$.