# The non-classical effects of photoelectrons emitted from a nickle plate under electromagnetic radiation of different colors

Thresa Kelly and Michael Murray
*University of Kansas, PHSX 616 Physical Measurements*
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The classical theory of electromagnetism states that light is an electromagnetic wave which can interact with electrons. It predicts that a light continuously transfers energy to a material, which can then release electrons when they accumulate enough energy. However, recent studies suggest that the color of light is instead a packet with a quantized amount of energy. Under this model, photoelectrons could only be released from a metal if the single light quanta stores enough energy. To investigate this controversy, I measure the current across a photodiode for variable colors and intensities of light from a mercury (Hg) bulb. I find that the breaking potential energy has a linear relationship with the wavelength of the incident light and is unchanged by the intensity of incident light. This disproves the prediction of the classical theory and shows that light consists of packets of quantize energy, or photons.

## I. INTRODUCTION

In 1865, James Clerk Maxwell demonstrated that light behaves like electromagnetic wave oscillating between electric and magnetic fields [1]. The electromagnetic wave equations are written as

$$\left(v_{\text{ph}}^2\nabla^2 - \frac{\partial^2}{\partial t^2}\right)\mathbf{E} = \mathbf{0} \tag{1}$$

$$\left(v_{\text{ph}}^2\nabla^2 - \frac{\partial^2}{\partial t^2}\right)\mathbf{B} = \mathbf{0} \tag{2}$$

where $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, and $v_{\text{ph}}$ is the phase velocity. The solution to the $v_{\text{ph}}$ is equal to the experimental measurements for the speed of light $c$. Thus, the speed of light $c$ is a function of the with permittivity $\varepsilon_o$ and permeability $\mu_o$ as follows.

$$v_{\text{ph}} = \frac{1}{\sqrt{\mu_o\varepsilon_o}} = 2.99792\times 10^8\, m/s = c \tag{3}$$

These waves propagate through space at a certain wavelength ($\lambda$) and carry energy. According to this classical theory, light can transfer its energy into a metal causing it to release photoelectrons after the electrons absorb enough energy. Therefore, increasing the intensity of the incident light should increase the number of freed electrons. However, some studies have shown that the photoelectron emission may be dependent on the color of light: Heinrich Hertz discovered in 1887 that an electric spark produced under radiation was strongest for ultraviolet light [2], and Wilhelm Hallwachs demonstrated in 1888 how an electroscope would react stronger to ultraviolet light [3].

In his 1901 paper, Max Planck states that an oscillator [4] can only have energies at discrete energy levels. The oscillator can jump up an energy level when it absorbs the exact quanta of energy between the levels. Similarly, it can relax to a lower energy lavel by emitting the same quanta of energy. Planck writes that the energy $E$ is a function of a constant $h$ and the frequency $\nu$ or wavelength $\lambda$.

$$E = h\nu = h\frac{c}{\lambda} \tag{4}$$

Electromagnetic radiation oscillates between electromagnetic and electric fields. Thus, light may be quantized by its color.

In this research, I investigate how the number of photoelectrons freed from a metal plate under incident light change with respect to the color and intensity of incident electromagnetic radiation. I observe how the 365, 405, 435, 546, and 577 nm emission lines from a mercury (Hg) bulb affect the current through a photodiode with an adjustable aperture and power supply.

## II. METHOD

I use the SE-6609 Photoelectric Effect Apparatus by PASCO [5]. The diagram of the apparatus is shown in Figure 1. The main components of the apparatus consists of the light source enclosure, photodiode enclosure, direct current (DC) current amplifier, and DC power supply. PASCO states that the current amplifier is highly sensitive, the photodiode has low levels of dark current and anode reverse current, and the optical filters are high quality [5]. The light source is a mercury (Hg) bulb, which has emission lines at 365, 405, 435, 546, and 577 nm. Each of these emission lines can be isolated by selecting one of the five filters to cover the photodiode aperture. The aperture size can be set to Ø2, Ø4, and Ø8. The nickel photodiode has a spectral response range of 300-700 nm, which covers all of the Hg emission features. The photodiode tube has a minimum cathode sensitivity $\geq 1$ $\mu$ m/Lm and a dark current $\leq 20\times 10^{-13}$ A. The DC current amplifier can measure currents between $10^{-8} - 10^{-13}$ A, and the decimal precision is set using a dial; it also has a calibration knob to zero the measured current. The photodiode DC power supply can provide voltages between $-4.5$ to 30 V.

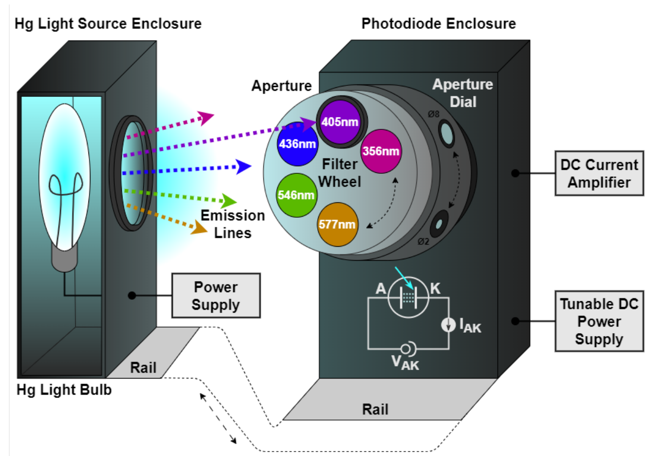


FIG. 1. Photoelectric effect apparatus [5]. The apparatus consists of two enclosures, one for the mercury (Hg) light source (left) and the other for the photodiode (right). The Hg bulb is controlled by a power supply. Light from the bulb is directed toward the photodiode by passing through a hole in the Hg light source enclosure and entering the filtered aperture of the photodiode enclosure. The filter and aperture can be changed by turning the filter wheel and aperture dial, respectively. An external device measures the DC current of the photodiode and controls the photodiode's DC power supply.

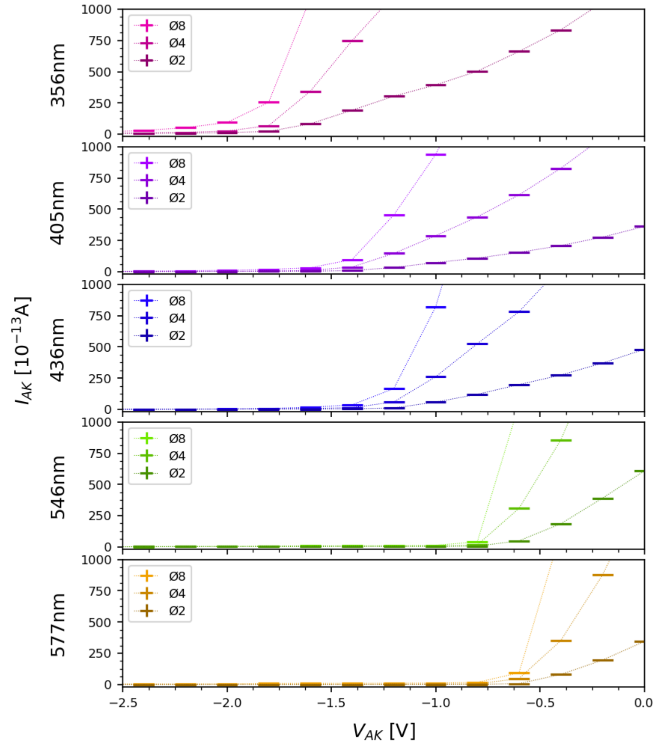


FIG. 2. DC current across the photodiode $I_{AK}$ for a DC power supply $V_{AK}$ for colors and intensities. Data for each 365, 405, 435, 546, and 577 nm wavelength filter is colored pink, purple, blue, green, and yellow respectively. The vertical error bars on the data points are small. A dotted line is drawn between each measurement in their respective series. The intensity is highest for the Ø8 and weakest for Ø2 aperture. Each wavelength has a different minimum voltage.

The apparatus allows the user to measure the number of electrons freed from nickel metal by incident electromagnetic radiation. Light enters the filtered aperture and strikes photodiode cathode. The electromagnetic radiation then transfers its energy to the nickel and frees electrons to move to the anode; this generates a current, $I_{AK}$, through the circuit. The electric potential energy difference across the anode, $V_{AK}$, determines the amount of energy required for the electrons to overcome in order to move across the diode.

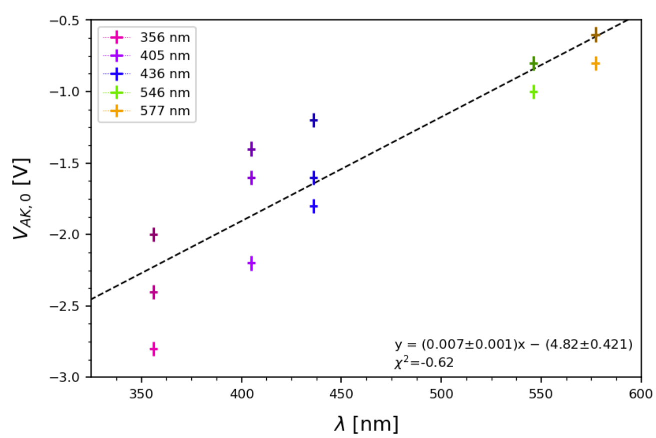


FIG. 3. Breaking voltage across the photodiode ($V_{AK,0}$) for the five wavelength ($\lambda$) filters and three intensities (Ø8, Ø4, and Ø2). In each set of three points of one color, the largest intensity (Ø8) is the brightest colored point. The $V_{AK,0}$ appears to have a positive linear correlation to wavelength.

## III. RESULTS AND DISCUSSION

In this research, I observe the relationship between the color and intensity of electromagnetic radiation. I claim the following uncertainties: $V_{AK}$ is $\pm 0.05$ V, $I_{AK}$ is $\pm(2\times 10^{-X})$ A where $X$ is magnitude setting on the current amplifier, and the wavelength is $\pm$ 0.5 nm.

Figure 2 shows how the current-voltage response changes with the wavelength of the electromagnetic radiation. For all colors, the current begins at zero before exponentially increasing. Increasing the aperture of the apparatus increases the intensity of incident radiation, which causes a large increase in the current through the detector. The five colors differ in the voltage where the current goes to zero, called the stopping potential ($V_{AK,0}$).

To further investigate the stopping potential response, I extract the voltage point where the difference between two currents is greater than $2 \times 10^{-13}$ A. This marks

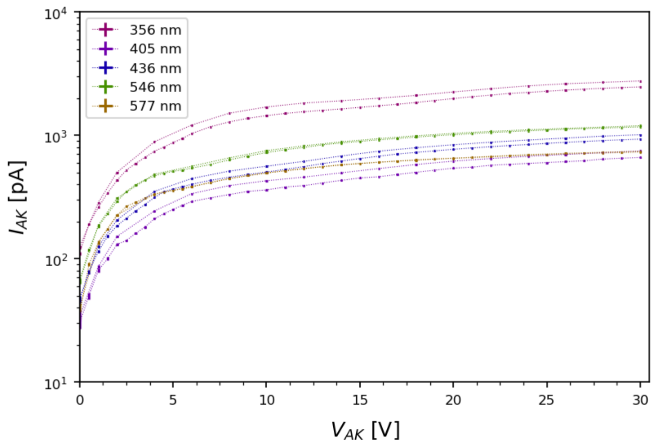


FIG. 4. DC current across the photodiode $I_{AK}$ for a DC power supply $V_{AK}$ for five different colors of light. The aperture is set to Ø2. The second trial data set is slightly darker than the first trial. The error bars are small and difficult to resolve. Each wavelength has a different maximum current at large voltage.

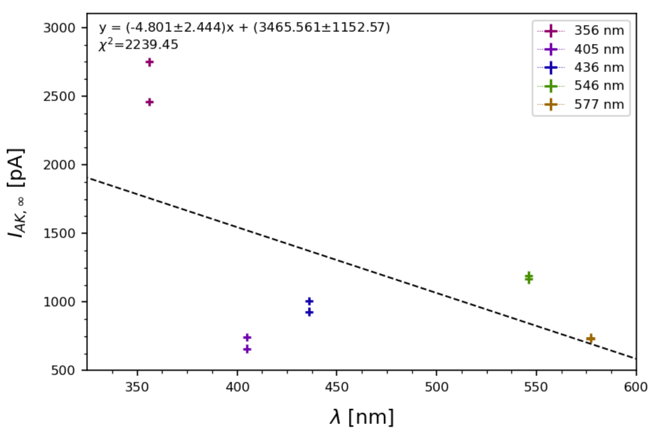


FIG. 5. Maximum current across the photodiode ($I_{AK,\infty}$) for the five wavelength ($\lambda$) filters. The aperture is set to Ø2. The second trial data is colored darker than the first trial. Current and wavelength do not have a linear correlation, shown by the very large $\chi^2$.

where the slope begins to increase above the noise around zero. The results are shown in Figure 3. The breaking voltage $V_{AK,0}$ appears to have a positive correlation with wavelength. Using a linear regression fit yields the equation

$$V_{AK,0}[V] = (0.007 \pm 0.001) \cdot \lambda \\ -(4.8 \pm 0.4)[V] \tag{5}$$

relating the stopping potential to wavelength, with intercept describing the work function. The equation yields a $\chi^2 = -0.58$ showing that the linear fit yields a good fit to the data.

Next, I investigate the current behavior for positive voltages. Figure 4 shows the current for 0.0−30.0 V. For positive voltages, the slope decreases until the current levels off to a constant $I_{AK,\infty}$. Then, I investigate how the current threshold relates to the color of the incident light. To do this I extract the maximum current, which occurs at $I_{AK,\infty} = I_{AK}(V_{AK} = 30V)$. I plot the $I_{AK,\infty}$ as a function of wavelength in Figure 5. A linear fit does not well represent the data, as the $\chi^2$ is very large. It is highly unlikely that the magnitude of the current relates to the color of electromagnetic radiation. The differences in current are more likely due to the intensity of the emission line from the Hg bulb.

## IV. CONCLUSION

The goal of this research was to determine how the color and intensity of electromagnetic radiation affects the number of electrons freed from a nickle plate under the incident light. To investigate these effects, I use an apparatus that shines a mercury (Hg) bulb through one of five wavelength filters–365, 405, 435, 546, and 577 nm, each corresponding to an Hg emission line–and an adjustable aperture into a photodiode. I then measure the current of electrons scattered off of the nickle anode for voltages between −4.5 to 30.0 V.

I observe that the current only begins to increase once the voltage is greater than a stopping potential, $V_{AK,0}$. This potential energy difference is unique to each colored filter and has a strong positive correlation with wavelength. After overcoming this threshold, the current quickly increases with voltage before dropping off to some constant current $I_{AK,\infty}$. This maximum current is not related to the wavelength of light. The differences in magnitude are more likely due to the intensity of the emission lines from the Hg bulb.

The experimental results of this photoelectric effect disprove the prediction of classical electromagnetism. Under the classical model, the number of emitted electrons should only increase with the intensity of incident light. However, the data shows that the number of photoelectrons is dependent on the wavelength of light, not the intensity. Max Planck has shown that oscillators are quantized [4]. Therefore, the electrons emitted by the photodiode must only be release if they absorb a certain quanta of energy. This energy packet must be dependent of the color of incident light. Thus, light must not simply be a continuous wave of electromagnetic radiation, but by a wave packet.

## V. IMPROVEMENTS

Here is a list of the improvements from the previous draft of this research paper: (1) completed the introduction to better explain the significance of the experiment, (2) took more data for negative voltages to better constrain the stopping potential, (3) performed additional trials for different light intensities, (4) expanded the conclusions, and (5) fixed formatting and grammar problems.

[1] J. Maxwell and T. Torrance, *A Dynamical Theory of the Electromagnetic Field*, Torrance collection (Wipf and Stock, 1996).

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[3] W. Hallwachs, Ueber den einfluss des lichtes auf electrostatisch geladene körper, Annalen der Physik **269**, 301 (1888), https://onlinelibrary.wiley.com/doi/pdf/10.1002/andp.18882690206.

[4] M. Planck, Ueber das gesetz der energieverteilung im normalspectrum, Annalen der Physik **309**, 553–563 (1901).

[5] PASCO, *Photoelectric Effect Apparatus: Model No. SE-6609* (PASCO, 2023).