Experiments in Physics
**Lab – The Photoelectric Effect – PhET simulation**

Name **Key**_____ Score_____

Introduction: In 1905 Max Planck, a German theoretical physicists, proposed a mathematical solution to what was known as the ultraviolet catastrophe with regards to the emission of electromagnetic radiation from a blackbody. Max Planck showed that the energy of light was quantized or came in discrete packets called "quanta". The energy of a photon was given by $E = hf$ where h is Planck's constant $\left(6.63 \times 10^{-34} J \cdot s\right)$ and f is the frequency of the light. The development was unexpected given that light was known to travel as a wave implying that light is not quantized. It had been clearly shown that light interferes much like sound and water waves. It wasn't until 1905 that Albert Einstein used Planck's equation to describe the minimal element of electromagnetic radiation called a "photon". Einstein used $E = hf$ to explain photoelectric emission or the photoelectric effect. The purpose of this lab is to determine and use the mathematical expression that represents the photoelectric effect. In addition, an understanding of the wave-particle duality of light will be developed.

Part I – Stopping Voltage
Introduction: When an electron has a certain amount of kinetic energy inside an electric field a potential difference can be applied to "stop" the electron. The amount of energy or work needed to stop the electron is given by

$W = Vq$ from the definition of potential difference -- $\Delta V = \dfrac{\Delta W}{q}$. Recall that $1 eV = 1.60 \times 10^{-19} C$.
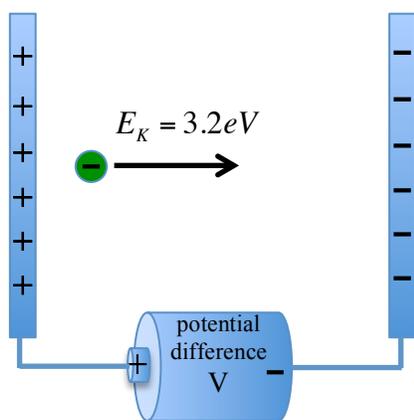
(1) How much potential difference or stopping voltage would be required to "stop" an electron with a kinetic energy of 3.2 eV traveling in the electric field shown on the right? Show all your work.

$E_K = 3.2 eV$

V=(3.2eV * 1.6E-19J/eV)/(1.6E-19C)=3.2V :)

(2) If the stopping voltage for an electron is -2.7V, how much kinetic energy does the electron have in Joules?

W=(-2.7V)*(1.6E-19)=4.3E-19J

Part II – The Photoelectric Effect
(1) When the light shines on the surface of a metal, the light **may** eject electrons from the metal with additional kinetic energy. To determine how much kinetic energy is being given to the electrons from the photons of light, a set of parallel plates was setup in a vacuum. One plate consisted of the metal that would be exposed to different wavelengths or frequencies of light. The plates were also connected to a source of potential difference or voltage. The entire apparatus represented a complete circuit. If the light was able to eject electrons from the metal it would cause a current to flow in the circuit – shown by an ammeter. The battery or source of potential difference may be adjusted to "stop" the current or cause the current to fall to zero. ***The potential difference applied to stop the current is equivalent to the kinetic energy of the electron that was ejected by the light shining on the metal.*** The apparatus is reproduced in the PhET simulation entitled "Photoelectric Effect 1.10". Open the PhET simulation and explore the simulation.
(2) We will begin by exploring how the intensity of light affects the stopping voltage in the experiment. Complete the table below by setting the appropriate parameters. **Under options, select "Show photons".**

Metal	Wavelength/nm	Intensity/%	Current when Voltage is 0 /A	Stopping Voltage**/ V	Calculate E_K for the electron **in Joules**
Sodium	400	50	0.071	-0.78	1.25E-19
Sodium	400	75	0.106	-0.78	1.25E-19
Sodium	400	100	0.141	-0.78	1.25E-19

(3) Based upon your results for item (2) answer the following questions:

    a. Explain why the current increased when the intensity of the light changed? (Hint: How is the number of photons in the light related to the intensity of the light and how does this relate to the definition of current?)

> The intensity of light is proportional to the number of photons striking the metal (i.e. I=0.07A at 50% intensity, I=0.14A at 100% intensity). As more photons strike the metal, more electrons are ejected from the metal surface. As a result, there are more charges passing through the circuit in a given time period.

    b. Does the intensity of light have any effect on the maximum kinetic energy of the electrons? What does this tell you about the energy associated with each individual photon? Explain. Is this consistent with Max Planck's mathematical model that light comes in discrete packets of energy called "quanta". Explain.

> The intensity of light has no effect on the maximum kinetic energy of the ejected electrons. Light of a given wavelength has a discrete amount of energy. As a result, the maximum kinetic energy of the electron is a discrete value given that the orbital energy is also discrete.

(4) One key feature of photoemission that supports Max Planck's idea that light comes in discrete packets involves an important observation with regards to the frequency of light that causes photoemission. The next investigation will look at the influence of changing the wavelength of light shining on the metal. The observation was crucial to Einstein's mathematical explanation of photoemission. Complete the table below by changing the necessary parameters. Check the box entitled "Show only highest energy electrons" and set the intensity to 100%. **The wavelength and stopping voltage can be changed to specific values by clicking on the boxes near the slider. Be careful to determine the stopping voltage to the nearest 0.01 V. Adjust the voltage such that the ejected electrons stop just short of the negative plate. If the electrons hit the negative plate, the stopping voltage must be increased – try 0.01 increments when getting close.**

Metal	Wavelength/nm	Calculate the frequency using $f = \dfrac{c}{\lambda}$ / Hz	Stopping Voltage/ V	Calculate the maximum kinetic energy ($E_{K(max)}$/ J)
Sodium	125	2.4 x 10^{15}	-7.57	1.21E-19
Sodium	300	1.0 x 10^{15}	-1.79	2.86E-19
Sodium	450	0.67 x 10^{15}	-0.33	0.53E-19
Sodium	538	0.558 x 10^{15}	-0.01	0.002E-19
Sodium	540	0.556 x 10^{15}	0	no ejection

(5) Describe what happens to the stopping voltage for wavelengths greater than or equal to 540 nm. Based upon your knowledge of the atom, hypothesize an explanation for such behavior.

> No stopping voltage is required because no electrons are ejected from the metal. The atom's outer most electrons are bound to the atom and require a minimum amount of energy to remove them from their orbit. Wavelengths greater than or equal to 540nm do not have enough energy to eject the electrons.

(6) At 540nm no electrons are ejected. The frequency or wavelength at which electrons are just barely ejected from the metal is referred to as the threshold frequency, f_0. Suggest what the threshold frequency might be for the Sodium metal? __0.558E15 Hz (538nm)__

(7) If light travels as a wave, according to classical electromagnetic field theory, electrons should be able to be ejected from a metal at **any frequency or any intensity** – since light would consist of a continuous stream of energy. How does the existence of a threshold frequency support Max Planck's quantum theory of light proposed by $E = hf$?

> The existence of a threshold frequency suggests that light is not a continuous stream of energy, but comes in discrete packets. The amount of energy in each "packet" is given by Max Planck's equation, E=hf, where h is Planck's constant. The amount of energy in light is proportional to the frequency of the light.

(8) Einstein won the Nobel Prize in Physics in 1921 for his mathematical interpretation and explanation of the photoelectric effect in terms of the "quanta" of light.

> In fact, it seems to me that the observations on "black-body radiation", photoluminescence, the production of cathode rays by ultraviolet light and other phenomena involving the emission or conversion of light can be better understood on the assumption that the energy of light is distributed discontinuously in space. According to the assumption considered here, when a light ray starting from a point is propagated, the energy is not continuously distributed over an ever increasing volume, but it consists of a finite number of energy quanta, localised in space, which move without being divided and which can be absorbed or emitted only as a whole.
>
> Albert Einstein, 1905

Interestingly, Sir Isaac Newton firmly believed that light was a particle and Newton's "corpuscle" or "little particle" theory of light was the predominant theory of light for over 100 years. Newton published "Opticks" in 1704 explaining the corpuscular theory of light. The modern understanding of light is represented by the wave-particle duality. In other words, light travels as a wave and behaves like a particle at the same time! Name three more observational phenomena that clearly show that light behaves as a wave.
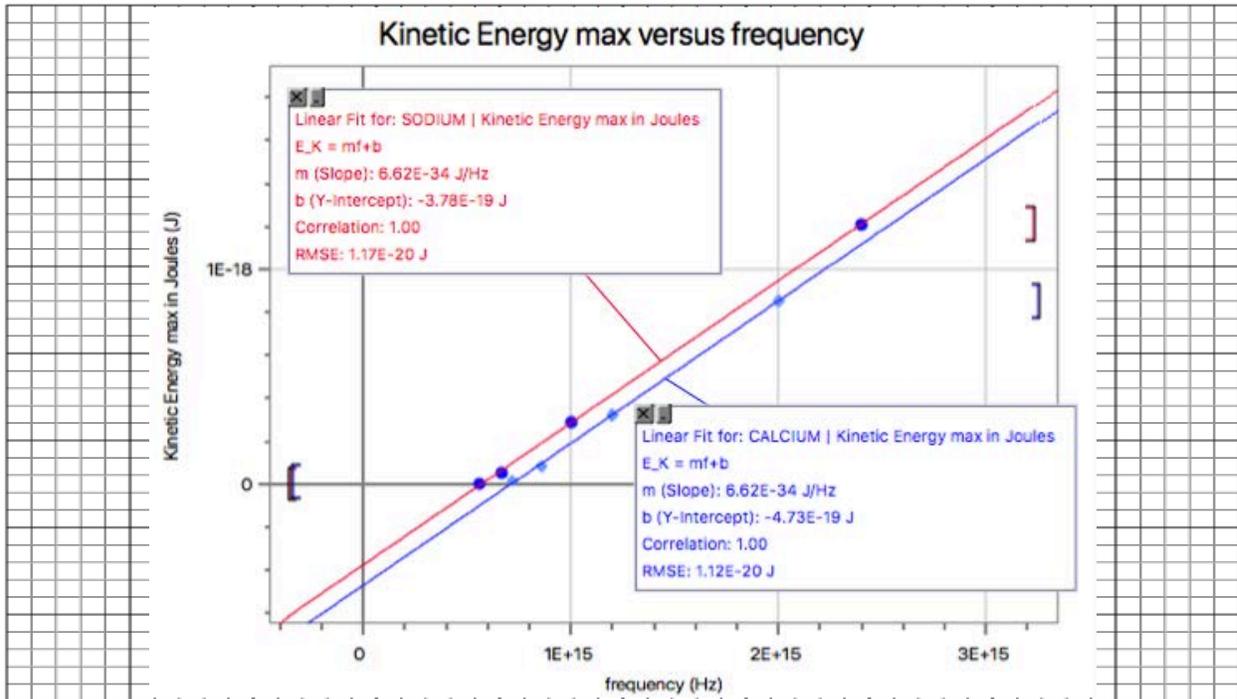
a. __Young's double slit experiment- diffraction pattern__

b. __polarization of light__

c. __thin film interference__

(9) According to atomic theory, electrons are bound to the nucleus of the atom because of the electrostatic attraction between with the positive nucleus of the atom. If an electron is given enough energy, the electron will leave the atom, ionizing the atom. The work function for an atom is the minimum amount of energy needed to remove an electron to infinity from an atom (usually a metal) and is given by the Greek letter ϕ.

Based upon the data from item (4) and using $E = hf$, calculate the work function for Sodium in eV and joules. Show all your work.

> E=(6.63E-34J*s)*(0.558E15Hz)=3.7E-19J
> 3.7E-19J*(1eV/1.6E-19J)=2.3eV

(10) Using the data in item (4) graph the maximum kinetic energy of the electron versus the frequency of the light using Logger Pro, Excel, or another graphing program. Sketch and annotate the graph on the grid below. Make sure to label the axis, x-intercept, y-intercept, and the slope of the best-fit line. What is the value of the slope? 6.62E-34J*s___. What does the quantity represent? Planck's constant___

Kinetic Energy max versus frequency

Linear Fit for: SODIUM | Kinetic Energy max in Joules
E_K = mf+b
m (Slope): 6.62E-34 J/Hz
b (Y-Intercept): -3.78E-19 J
Correlation: 1.00
RMSE: 1.17E-20 J

Linear Fit for: CALCIUM | Kinetic Energy max in Joules
E_K = mf+b
m (Slope): 6.62E-34 J/Hz
b (Y-Intercept): -4.73E-19 J
Correlation: 1.00
RMSE: 1.12E-20 J

(11) Photoemission, the ejection of an electron, occurs when an electron absorbs the energy of a photon. If the frequency of the light is high enough, referred to as the threshold frequency (as seen in item (5)), the electron will leave the surface of the metal. Any extra energy beyond the work function for the electron is given to the electron as kinetic energy. The maximum kinetic energy is a result when the outmost electron, the electron with the smallest work function (phi), is ejected from the metal. Write an equation in the form of y = mx + b to describe the line drawn in item (10).

$$E\_K = hf + phi$$

(12) Complete the table below and graph the maximum kinetic energy versus frequency on the same grid given in item (10). Annotate and label the graph appropriately. What is the value of the slope? 6.62E-34J*s___

Metal	Wavelength/nm	Calculate the frequency / Hz	Stopping Voltage/ V	Calculate the maximum kinetic energy ($E_{K(max)}$)/ J)
Calcium	150	2.0 x 10^{15}	-5.33	8.5E-19
Calcium	250	1.2 x 10^{15}	-2.01	3.2E-19
Calcium	350	0.86 x 10^{15}	-0.53	0.85E-19
Calcium	415	0.72 x 10^{15}	-0.09	0.14E-19
Calcium	428	0.70 x 10^{15}	0	no ejection

(13) Using your knowledge of atomic theory, postulate as to why the graph for Calcium has a different threshold frequency than Sodium.

Calcium and Sodium have difference numbers of protons resulting in different electrostatic attractions between the orbiting electrons. As a result, the work function for each element is different.

Part III – Problems on the Photoelectric effect

(1) State **one** aspect of the photoelectric effect that **cannot** be explained by the wave model of light. Describe how the photon model provides an explanation for this respect. (IB May 03 S(3))

    a. Aspect:

the existence of a threshold frequency

    b. Explanation:

Light consists of photons whose energy is the product hf. No electrons will be emitted unless hf is larger than the energy required for the electron to escape the metal.

(2) Light is incident on a metal surface in a vacuum. The graph below shows the variation of the maximum kinetic energy, E_{max} , of the electrons emitted from the surface with the frequency, f , of the incident light.
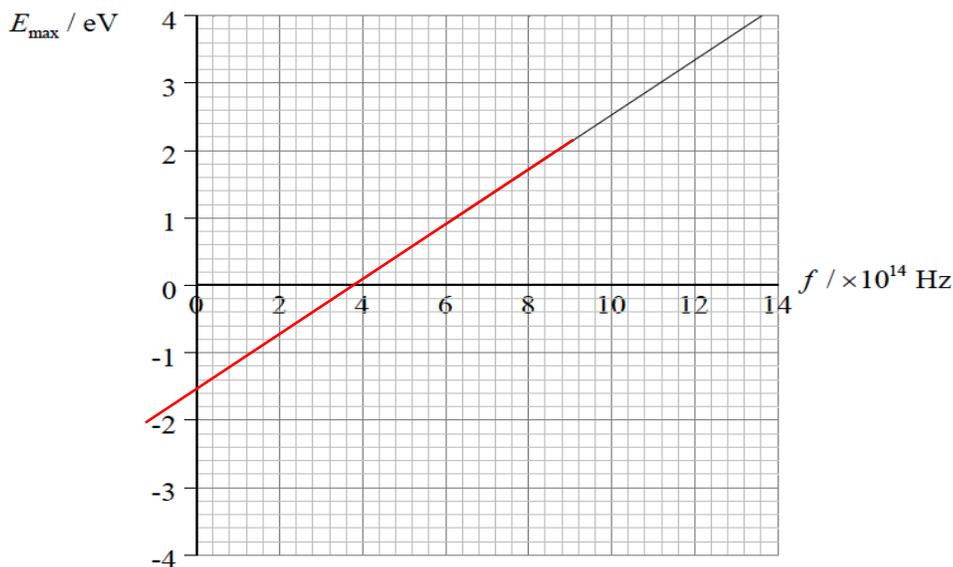
    a. Use data from the graph to determine the threshold frequency for the metal.

the x-intercept is the threshold frequency = 3.6E14 Hz

    b. Use data from the graph to determine the value of Planck's constant. Show all your work.

(slope*(1.6E-19)
two points chosen on the line -- (6E14,0.9eV) and (13.2E14,3.8eV)
=6.44E-34J*s

    c. Use data from the graph to determine the work function for the metal. Show all your work.

The work function is represented by the y-intercept = -1.5eV