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Part 1: PhET Virtual Experiment (Conceptual Analysis)

Tools needed: Computer with internet access.
Link: PhET Photoelectric Effect Simulation

1.1 The Setup

Open the simulation. You will see a lamp, a battery, and a vacuum tube containing two metal plates.

1. Set the **Target** to **Sodium**.
2. Set the **Intensity** to 50%.
3. Adjust the **Wavelength** until electrons are ejected.

1.2 Qualitative Predictions and Observations (18 pts)

1. (4 pts) **Suppose you set up the experiment so that the plate is ejecting electrons.** Predict which of the following changes to the experiment could **increase the maximum initial kinetic energy** of the ejected electrons. (Select all that apply) Then test your prediction. (Based on the photon model of light)

   - ☐ A. Increasing the intensity of the light beam
   - ☐ B. Decreasing the intensity of the light beam
   - ☐ C. Increasing the wavelength of light
   - ☑ D. Decreasing the wavelength of light
   - ☑ E. Increasing the frequency of light

   Do the same thing

   - ☐ F. Decreasing the frequency of light
   - ☑ G. Increasing the voltage of the battery
   - ☐ H. Decreasing the voltage of the battery
   - ☐ I. Replacing the target with a material that has a larger work function
   - ☑ J. Replacing the target with a material that has a smaller work function

   * All predictions were correct!

2. (4 pts) **Suppose now you set up the experiment so that the light intensity is non-zero but the plate is NOT ejecting electrons.** Predict which of the following changes to the experiment could **make the plate start ejecting electrons**? (Select all that apply) Then test your prediction. (Predictions based on the photon model of light)

   - ☐ A. Increasing the intensity of the light beam
   - ☐ B. Decreasing the intensity of the light beam
   - ☐ C. Increasing the wavelength of light
   - ☑ D. Decreasing the wavelength of light
   - ☑ E. Increasing the frequency of light
   - ☐ F. Decreasing the frequency of light
   - ☐ G. Increasing the voltage of the battery

☐ H. Decreasing the voltage of the battery

☐ I. Replacing the target with a material that has a larger work function

☑ J. Replacing the target with a material that has a smaller work function

(All predictions were correct!)

3. **(2 pts) What causes the electrons to be ejected from the left plate in this simulation?**

   ○ A. The force exerted on the electrons by the battery

   ● B. The beam of light shining on the plate

   ○ C. Both A and B.

   ○ D. Neither A nor B.

4. **(4 pts) (Short Essays) Photon Model vs. Wave Model.** For each scenario below, explain what you observe, what conclusions you can draw about light, and how it is consistent/inconsistent with the classical wave model vs. the photon model.

   a. Light is shining on a metal and electrons are being emitted. You turn the intensity down very, very low. (2pts)

   It is observed that the number of electrons being emitted decreases significantly, but their speed does not change. This is inconsistent with the wave model of light because a higher intensity should mean larger amounts of energy is being imparted on the electrons, which should cause the emitted electrons to speed up. This is consistent with the photon model of light since a greater intensity corresponds to more photons with the same amount of energy impacting the material, which are absorbed on an all-or-nothing basis.

   b. Light is shining on a metal plate and electrons are being emitted. Without changing the intensity, you make the wavelength longer and longer. (2 pts)

   It is observed that the number of electrons being emitted decreases significantly, and the speed of those electrons decreases as well. This is inconsistent with the wave model of light because decreasing the frequency should not change the amount of energy being carried by the light wave. This is consistent with the photon model of light because decreasing the frequency decreases the energy of the photons, given by $E = h\nu$. As the photons are absorbed on an all-or-nothing basis, fewer electrons will be ejected by these lower energy photons, and the ones that are will have less kinetic energy after being emitted.

5. **(1 pt each) True or False?** If the experiment is set up so that electrons are being emitted, which of the following are true?

T / F As long as conditions do not change, all emitted electrons have the same initial kinetic energy.

T / F The work function for the metal is different for different electrons. (The work function is based on the minimum amount of energy required to remove AN electron from the material)

T / F The energy of the photons hitting the plate must be less than the work function of the metal.

T / F The electrons emitted with the largest initial kinetic energy are those that were the least tightly bound in the metal.

1.3 Stopping Potential (22 pts)

6. **Graph Analysis**

In the photoelectric effect experiment, the graph of current vs. battery voltage for a metal with light of a particular frequency shining on it looks like the curve below. This graph represents current vs. voltage for 200nm light shining onto Cadmium (Cd) which has a work function of 4.07 eV.

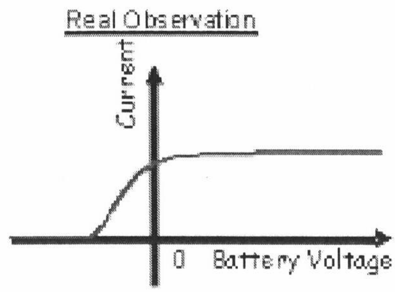


Figure 1: Current vs Voltage for 200nm light on Cadmium

(a) **(5 pts) (Essay)** Explain your reasoning for why this curve has the shape that it does. Address: Why is current level at $V > 0$? Why does current go to zero at some negative voltage? Why does current start decreasing steadily at $V < 0$?

- The current level becomes constant at higher positive voltages because the current is bounded by an upper limit of the number of electrons being ejected from the metal per second, which is determined by the frequency and intensity of light, not the voltage. Once basically all of the electrons emitted are hitting the anode, increasing the voltage increases the speed of the received electrons, but not the number of received electrons per second, so current remains unchanged.
- For $V<0$, the current starts decreasing steadily because the negative voltage is causing some electrons to turn around and never reach the anode, decreasing the current. The number of electrons that reach the anode per second is roughly proportional to the voltage in this case.
- The current goes to zero at some negative voltage because, at this voltage, even the electrons with the highest kinetic energies are forced to turn around, so no electrons reach the anode and the current drops to zero

eV are a unit for energy, not voltage...

(b) **(2 pts)** What is the stopping potential in this situation (in eV)? (Remember stopping voltage is expressed as a positive number).

$$V_{stop} = \frac{hf - E_0}{e} = \frac{(4.14\cdot10^{-15}\,eV\cdot s)\left(\frac{3\cdot10^{8}\,m/s}{200\cdot10^{-9}\,m}\right) - 4.07\,eV}{e}$$

$c = \lambda f \Rightarrow f = \frac{c}{\lambda}$

$$\boxed{V_{stop} = 2.14\ \text{Volts}}$$

(c) **(11 pts) Comparative Graphs.** In the graphs below, the gray curve is always the same (Cadmium, 200nm). The red curves represent the result after a change in the experiment.

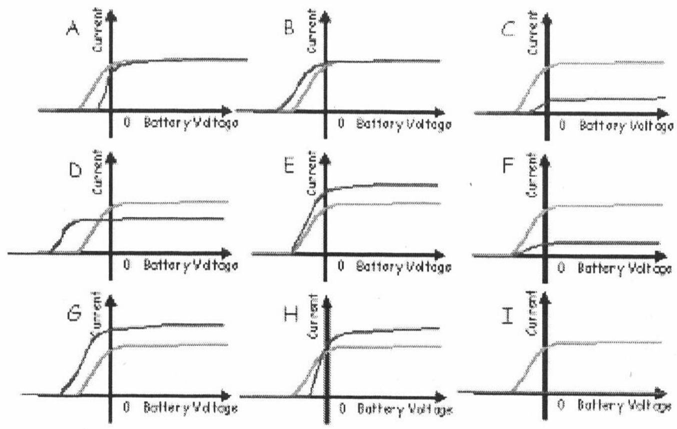


Figure 2: Multiple I-V Curves

i. **(2 pts)** If you decrease the wavelength of the light, (increase frequency) what happens to the voltage where the current goes to zero?

☑ Becomes a larger, negative number

☐ Becomes a smaller, negative number

☐ Is unchanged

Briefly explain your reasoning:

The stopping voltage can be calculated as $V_{stop} = \frac{hf - E_0}{e}$, and increasing frequency while keeping everything else constant would increase the magnitude of the stopping voltage

ii. **(1 pt)** Which graph would represent this decrease in wavelength? $\boxed{G}$

iii. **(1 pt)** Which graph would represent an increase in the intensity? $\boxed{E}$

iv. **(1 pt)** Which graph would represent an increase in wavelength to 290nm? $\boxed{C}$

v. **(1 pt)** Which graph would represent an increase in wavelength to 500nm? $\boxed{I}$

vi. **(1 pt)** Which graph would represent a switch to sodium? $\boxed{G}$

(d) **(4 pts)** What change or combination of changes would you need to explain the change observed in **Graph H**? (Check all that apply)

☐ Decrease in wavelength

☑ Increase in wavelength

☐ Decrease in intensity

☑ Increase in intensity

7. **(4 pts) Calculation Challenge.**
You have a colored spot light, but you don't know its precise wavelength. To find out the wavelength you shine your light on a sodium target ($\Phi = 2.3$ eV). If you set the battery voltage to -0.5 V, you find that the most energetic electrons nearly reach the right plate but turn around just before they get there.

What is the wavelength, in nm, of the colored light that you used?

$$V_{stop} = \frac{hf - E_0}{e} \Rightarrow \frac{V_{stop}e + E_0}{h} = f = \frac{c}{\lambda}$$

$$\Rightarrow \lambda = \frac{hc}{V_{stop}e + E_0} = \frac{(4.14 \cdot 10^{-15}\,eV\,s)(3 \cdot 10^{8}\,m/s)}{(0.5\,eV) + (2.28\,eV)} \Rightarrow \boxed{\lambda = 447\,nm}$$

1.4 The Threshold Frequency (20 pts)

8. **(3 pts) (Short Essay) Explain what the phrase - 'the work function for sodium' - means in a way that would make sense to a non-science person.**

   Imagine the electrons in the Sodium as balls in a pit. If I want to remove a ball from the pit, I have to give it a kick with enough energy so that it gets launched out of the pit. Obviously, balls deeper in the pit will require harder kicks to remove compared to higher balls. The work function in this analogy would be the least amount of energy I have to put into my kick to launch the highest ball in the pit out of the pit.

9. **Mystery Material Analysis**

   You have a plate of metal, but you have no idea what kind of metal it is. You decide to measure its work function by using it as the target in a photoelectric effect experiment. You can perform this experiment virtually by selecting '???' as the target in the simulation.

   (a) **(15 pts for Write Up)** What is the work function, in eV, of the mystery metal? Include a useful picture and explain your reasoning. Use the *Strategy*, *Solution*, *Significance* approach to solve this problem: describe appropriately the steps, highlighting how you make use of the PhET simulation. Show clearly the Maths steps and your reasoning. Generate a useful figure/picture that could be taken from the PhET simulation, and that would illustrate. You should submit this question on a separate sheet, along with the writeup of the 2 part of this project.

   [Writeup conducted on the following page]

   (b) **(2 pts) What is the mystery material?**

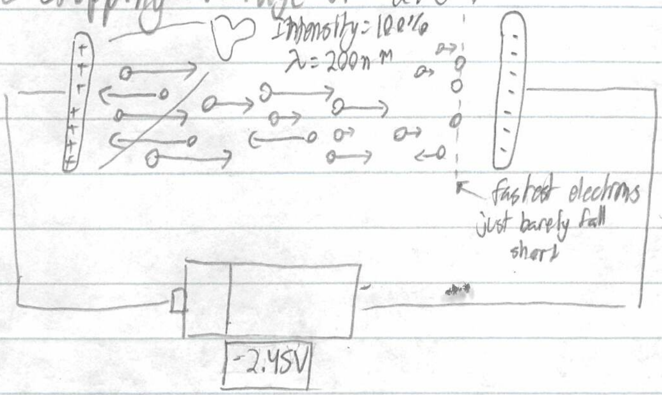
   - ○ Sodium (Na)
   - ○ Calcium (Ca)
   - ○ Cadmium (Cd)
   - ○ Aluminum (Al)
   - ○ Silver (Ag)
   - ○ Platinum (Pt)
   - ● Magnesium (Mg)
   - ○ Nickel (Ni)
   - ○ Selenium (Se)
   - ○ Lead (Pb) [cite: 66]

(Part 1: Question 9)

Mystery Material Analysis

Strategy

- We can set up an experiment where the wavelength of light is sufficient to get electrons to jump off of the material (and the intensity is not 0). Then, adjust the voltage until it is at a negative value where the fastest electrons just barely cannot reach the anode.
- Experimenting around, one way to do this is with 200nm wavelength light and a stopping voltage of 2.6 V:



- By finding the material's work function, we can get a guess for what the material should be.

Solution

$\lambda f = c \Rightarrow f = c/\lambda$

$$V_{stop} = \frac{hf - E_0}{e} \Rightarrow V_{stop}e = hf - E_0 \Rightarrow E_0 = hf - V_{stop}e$$

$$\Rightarrow E_0 = h\left(\frac{c}{\lambda}\right) - V_{stop}e \Rightarrow E_0 = (4.14 \cdot 10^{-15}\,eV \cdot s)\left(\frac{3 \cdot 10^{8}\,m/s}{200 \cdot 10^{-9}\,m}\right) - (2.45\,V)e$$

$\boxed{E_0 = 3.754\,eV}$ ← This closely matches the work function for $\boxed{\text{Magnesium}}$

Significance

This problem demonstrates how the photoelectric effect can be used as a method to determine what an unknown material is, without damaging the material, which is a highly interesting form of spectroscopy. This is only possible with the accurate formula for the energy carried by the photon, $E = hf$, which gives us one practical usage for the idea from quantum mechanics that light may sometimes behave like a particle. This idea may be used to gain information on a macroscopic scale.