The Photoelectric Effect

HISTORY

The year is 1905, and your name is Albert Einstein. 18 years ago, in 1887, Heinrich Hertz had discovered the ***photoelectric effect***, whereby electrons could be emitted from a material (especially a metal) by shining light on it. As of yet, however, nobody has been able to fully explain the process. This is where you come in.

Throughout the 19th century, starting in 1801 with Thomas Young and his double-slit experiment, scientists had explained many experiments involving light in terms of light acting as a wave. The ***wave theory of light*** could account for all sorts of light behavior, including reflection, refraction, thin-film interference, Young's double-slit experiment, as well as the diffraction experiments carried out by the French physicist Augustin Jean Fresnel in the early 19th century. The wave theory also explained the phenomenon called either the ***Arago spot*** or the ***Poisson spot***. Hearing about the wave theory of light, Simeon Poisson realized that if it were true the shadow cast by a round object would have a bright spot at its center. Poisson thought was ridiculous until Dominique Arago showed that such a bright spot existed.

The wave theory, in other words, was very successful at explaining all sorts of different experiments involving light. However, you, Albert Einstein, decide to build on the work of Max Planck. In 1900 Planck showed that the spectrum of radiated light emitted by an object at a particular temperature could be understood in terms of quantized energy levels. You extend this to propose a ***photon theory of light***, a model of light in which light is viewed as being made up of discrete bundles called ***photons***.

PREDICTIONS OF THE TWO THEORIES OF LIGHT

In the photoelectric effect, light shining on a metal surface can cause electrons to be emitted if the electrons absorb enough energy to overcome the binding energy that binds them to the surface. This binding energy, which depends on the metal, is called the **work function** W. Energy absorbed in excess of the binding energy is carried off by the electron as kinetic energy. Some of this kinetic energy may be transferred to other electrons or atoms in the metal. Because of this, we expect to observe electrons with a range of kinetic energies leaving the metal.

The wave theory

From the perspective of the wave theory, electrons absorb energy continuously because light is a continuous wave of electromagnetic energy. Specific predictions include:

- Increasing the light *intensity* (photon energy per second per unit area) increases the rate at which electrons leave the metal, and the electrons have more kinetic energy.
- Changing the frequency of the light while keeping the intensity constant should not change the rate of electron emission.
- Light of any frequency can cause electron emission.

The photon theory

In the photon theory, on the other hand, the energy of a photon is proportional to its frequency:

$E = hf$, where h is Planck's constant.

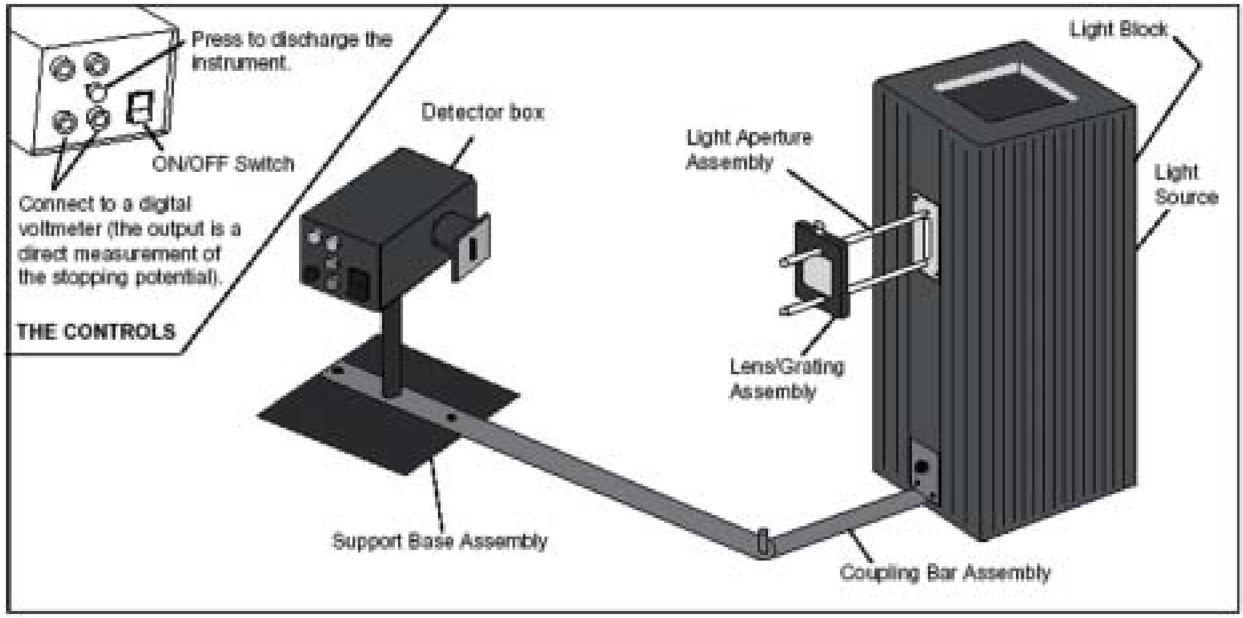
In this model the photoelectric effect can be understood in terms of interactions between individual electrons and individual photons, in which a photon can give up all of its energy to an electron. This leads to the following predictions:

- The photon energy must be greater than or equal to the work function W for electrons to be emitted. Photons with an energy less than W do not cause electrons to be emitted. Frequency, which determines the energy, is a critical factor.

- For a photon with an energy larger than the work function, the excess energy is carried off by the electron as kinetic energy. Thus, the maximum kinetic energy is:

  $KE_{max} = hf - W$

- Assuming the photon energy is sufficient to produce electron emission, increasing the intensity while keeping frequency fixed increases the number of photons hitting the metal, increasing the rate at which electrons are emitted but not changing the maximum kinetic energy of the electrons.



OBJECTIVES AND APPARATUS

The main goals of this experiment are to determine whether the wave theory or the photon theory match your observations about the photoelectric effect. You will make use of the following equipment:

- A Mercury Vapor Light Source. This mercury source is known to emit the following colors:

Color	Frequency (x 10^{14} Hz)	Wavelength (nm)
Yellow	• 5.19	• 578
Green	• 5.48996	• 546.074
Blue	• 6.87858	• 435.835
Violet	• 7.40858	• 404.656
Ultraviolet	• 8.20264	• 365.483

All values from the *Handbook of Chemistry and Physics, 46th edition*, except for the yellow line. The yellow line is actually a doublet (two lines), with wavelengths of 578 and 580 nm, and its wavelength was determined experimentally.

- A lens/grating assembly, mounted on the light source. The diffraction grating splits the light into three orders. You should remember from PY212 or PY252 that the angle at which a particular wavelength of light appears after passing through a diffraction grating is given by: $d \sin\theta = m\lambda$

- A photodiode detector, housed in the apparatus marked “h/e Apparatus AP-9368”.

- Green and yellow filters, to be placed on the white reflective mask in front of the photodiode when using the green and yellow lines, respectively. The filters prevent ambient room light from swamping the signals from the yellow and green light, and prevent the third-order ultraviolet line from overlapping the second-order yellow or green lines.

- A Variable-Transmission filter, to vary the intensity of the incident light. The filter can be set to pass 100%, 80%, 60%, 40%, or 20% of the light.

- A digital voltmeter, for recording the voltage from the photodiode.

EQUIPMENT SET-UP

Set up the equipment as shown in the diagram on the second page of this write-up. Note the following:

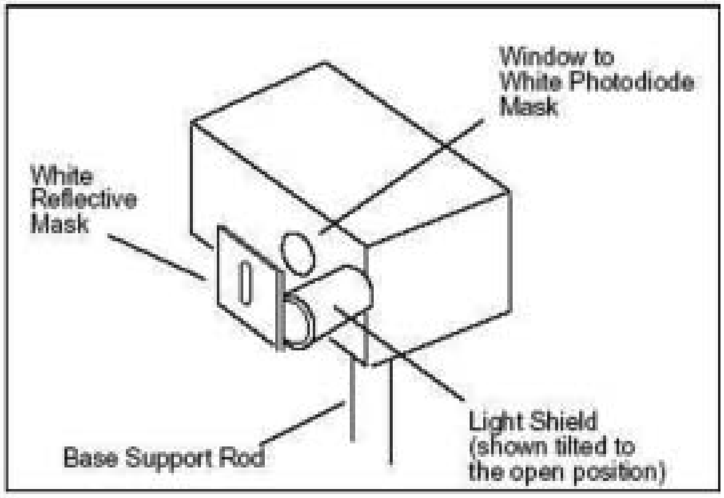
1. Turn on the light source and allow it to warm up for five minutes.

2. The detector uses two 9-volt batteries. Check the batteries by connecting one lead of the voltmeter to the ground terminal and the other lead to each battery test terminal, in turn, on the side of the detector box. One reading should be positive and the other negative – the absolute value of these voltages should be at least 6 volts. If not, get a fresh battery.

3. Connect the voltmeter to the OUTPUT terminals of the detector box. Use the 2-volt range on the multimeter.

4. Set the detector box directly in front of the mercury light. Slide the lens/grating assembly back and forth on its support rods until the light is focused on the white reflective mask.

5. Roll the detector light shield (see picture) out of the way to reveal the detector window. Rotate the detector box until the image of the aperture strikes the two small square windows in the photodiode mask.



6. Once again slide the lens/grating assembly back and forth until you achieve the sharpest possible image of the aperture on the photodiode window. Tighten the thumbscrew on the lens/grating assembly and replace the light shield.

7. Turn the detector power ON. Rotate the support-base assembly about the pivot until one first-order line shines on the slot in the reflective mask. Rotate the detector box on its support rod so that line falls on the two square windows in the photodiode mask (**make sure only one line shines on the windows**) and return the light shield to its closed position in front of the window**.** The reflective mask is fluorescent, making the ultraviolet line visible and the violet line more blue. Hold up a piece of paper to see the true colors.

8. Press the “PUSH TO ZERO” button on the side of the detector box. Don’t move the box!

9. Wait for the voltmeter reading to stabilize, and then read this output voltage. This is a direct measure of the maximum kinetic energy of the ejected electrons, in units of electron-volts. (See the next page for more details.) Note: for some set-ups the voltage may temporarily read high before dropping down to the true reading.

HOW THE DETECTOR WORKS

The photodiode contains a cathode with a low work function. Electrons ejected from the cathode (because of light shining on it) collect on the anode of the photodiode. The photodiode acts like a capacitor that is charged by the emitted electrons. When the capacitor voltage reaches the stopping potential (the voltage required to decrease the kinetic energy of the emitted electrons to zero) no more electrons reach the anode and the capacitor voltage stays constant. The final voltage across the photodiode (what you measure with the voltmeter) is the stopping potential, which is numerically equal to the maximum kinetic energy of the electrons if you measure that energy in electron-volts (eV). The "PUSH TO ZERO" button simply discharges the capacitor.

To let you measure the stopping potential with the voltmeter the anode is connected to a high-impedance ($>10^{13}\ \Omega$) unity-gain (Vout/Vin = 1) amplifier. The amplifier does slowly drain charge from the capacitor. Thus, charging the capacitor is analogous to filling a bathtub with water while the drain is partly open.

THE EXPERIMENT

PART I

First, investigate what happens when you change the intensity of the light reaching the photodiode. Now that you know how the detector works (see above) predict the answer to the following question:

Question 1: Will reducing the light intensity affect the time it takes the capacitor to reach its maximum charge? If so, how? Briefly justify your answer.

Question 2: According to the wave theory and the photon theory, what should happen as the intensity of the light is decreased?

1. Adjust the apparatus so one first-order spectral line falls on the photodiode. If you use the green or yellow line place the corresponding filter over the white reflective mask.

2. Place the Variable Transmission Filter over the white reflective mask (and over the colored filter, if you use one) so the light passes through the 100% section. Press and release the "PUSH TO ZERO" button. When the voltmeter reading stabilizes, record the voltage and the approximate time to stabilize in the table at the end of this write-up.

3. Repeat for the 80%, 60%, 40%, and 20% regions of the Variable Transmission Filter.

4. Repeat the process for another first-order spectral line.

Question 3: As you reduce the light intensity, what happens to the time taken to charge the capacitor in the detector circuit? Does this match your prediction from Question 1 above?

Question 4: Do the results of part I support the wave theory, the photon theory, both theories, or neither theory? Explain.

PART II

Now, investigate what happens when you change the frequency of the light reaching the photodiode.

Question 5: According to the wave theory and the photon theory, what should happen to the maximum kinetic energy of the emitted electrons as the frequency of the light is increased?

1 Remove the Variable Transmission Filter from the white reflective mask.

2 One at a time, record the maximum kinetic energy of the emitted electrons when each of the five first-order spectral lines illuminates the photo-diode. There is an appropriate table for your data at the end of this write-up. Remember to use the yellow and green filters for the yellow and green lines, respectively.

3 Repeat the process for the second-order spectral lines.

4 Plot a graph of the maximum kinetic energy of the electrons as a function of frequency. If you find the relationship to be linear, determine the slope, the x-intercept, and the y-intercept.

Question 6: Do the results of part II support the wave theory, the photon theory, both theories, or neither theory? Explain.

Question 7: Can you use your results to determine Planck's constant? If so, find it and compare your result to the accepted value.

Question 8: If you obtained a linear relationship in step 4 above, what is the significance of the graph's x-intercept?

Question 9: Can you use your result to determine the work function of the photodiode cathode? If so, what is the value? Work functions are usually stated in units of eV.

Question 10: Do you think you, Albert Einstein, deserve a Nobel Prize for your photon theory of light, based on the results of this experiment?

DATA TABLES

PART I

Color #1: ______________________________

% Transmission	Maximum Kinetic Energy (eV)	Approximate Charge Time (s)
100		
80		
60		
40		
20		

Color #2: ______________________________

% Transmission	Maximum Kinetic Energy (eV)	Approximate Charge Time (s)
100		
80		
60		
40		
20		

PART II

First-order Color	**Frequency (x 10^{14} Hz)**	**Maximum Kinetic Energy (eV)**
Yellow		
Green		
Blue		
Violet		
Ultraviolet		

Second-order Color	**Frequency (x 10^{14} Hz)**	**Maximum Kinetic Energy (eV)**
Yellow		
Green		
Blue		
Violet		
Ultraviolet		