Topic 18: Photons

Source: *Conceptual Physics* textbook, lab book and CPO Textbook and lab book

Types of Materials: Textbooks, lab books, worksheet, demonstrations, websites/videos and good stories

Building on: The concept of a photon was new and didn't build on anything. Previous ideas needed to understand the photon include wavelength, frequency, energy and the speed of light.

Photon Energy: $E = hf = hc/\lambda$ (where, $c = f\lambda$)

Leading to: A knowledge of photons is part of quantum mechanics including Einstein's photoelectric effect, pair production and the uncertainty principle. Atomic physics then explains atomic spectra, the workings of the hydrogen atom and lasers and holography. Nuclear physics can be seen in gamma ray production and part of the Standard Model.

Links to Physics: Items in "Leading to" are directly related to physics. Other applications of photons carrying energy include every part of the EM spectrum. Some examples for radio frequency (RF) are communications and appliances using RF signals like cellular telephones, cordless telephones, and baby monitors. Examples of microwaves include the oven, radar, communication and atomic and molecular study. Examples of infrared (IR) signals include heating matter, temperature sensors, IR cameras, physical therapy and IR astronomy. Visible light is used in many obvious topics like art, painting the walls of your home and seeing in general. Ultraviolet radiation (UV) can be used in photography, drinking water treatment, and treating fungal diseases of the skin. X-rays are used in medicine to check for broken bones and other internal fissures seen inside metal materials for cracks, and astronomy. Finally, gamma rays are used in astronomy for detection, but in general, the gamma ray is too dangerous to be around—causing human sickness and death. We are exposed to this radiation from outer space constantly, especially in air travel at a lower level, but it adds up.

Links to Chemistry and Biology: Electron configuration in atoms with different energy levels is useful when the energy is released upon transition between orbital and in photosynthesis with light energy being changed into chemical energy. Also, structural information about molecules is found using ultra-high-resolution beam lines.

Materials:

(a) Hewitt
Particular Waves

(b) Hsu
Energy and Quantum Theory

(c) My Lab*

(d) Worksheet
Energy Levels in a Fake Atom*

(e) Demonstration
Photoelectric Effect (3 Versions)

(f) Videos and Websites
Photon Lab Simulation

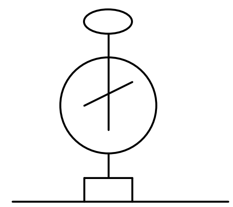
(g) Good Stories
Max Planck and a Lucky Guess

Topic 18: Demonstration – Photoelectric Effect

Theory: This simple and VISUAL demonstration shows that different frequencies of electromagnetic radiation possess different energies. Thus, frequency and energy of photons are directly related.

Materials:

(a) Sensitive display electroscope like from Leybold with a flat top attachment.

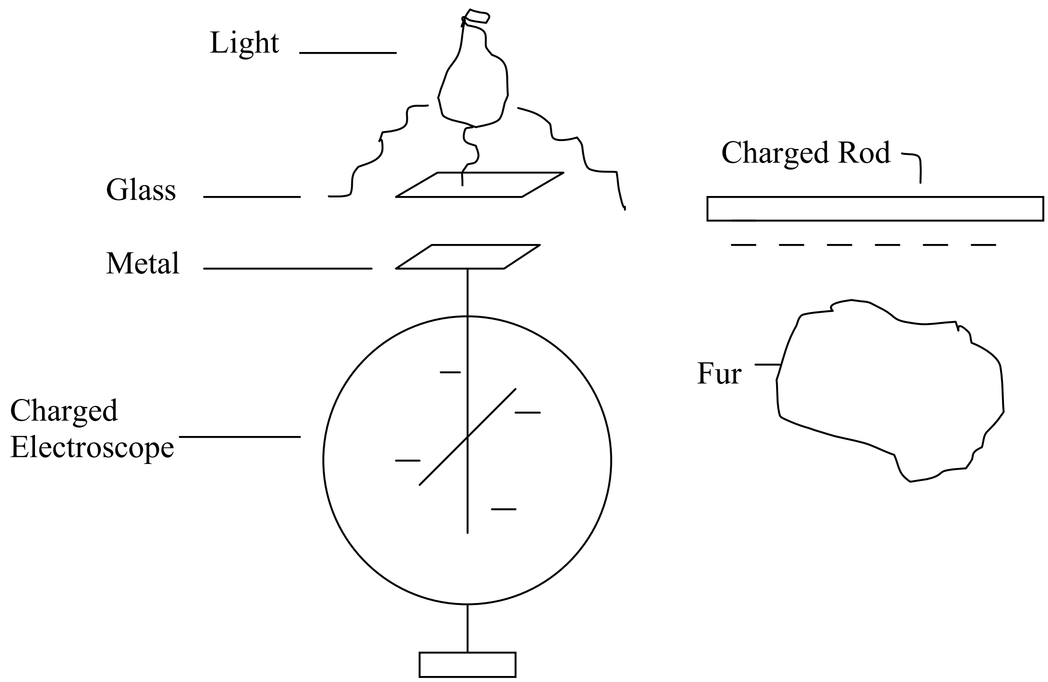


(b) Rabbit fur and acetate rod (-); glass rod and silk (+)
(c) Zinc and copper plates about 15 cm square and glass sheet about 15 cm square
(d) Emery cloth for sanding
(e) 100W light bulb, socket and plug-in wire
(f) UV light source with plug-in wire

Procedure: (Do this demo on a dry day and practice before the demo.)

1. Lightly sand the top plate of the electroscope and both sides of the two metal plates to expose pure metal.
2. Place the zinc plate on the top of the electroscope. Charge the electroscope negatively with the acetate rod rubbed on fur. The rod and scope have the same charge through conduction and that is negative by definition. To verify, bring the charged negative rod near the charged electroscope and the movable indicator spreads apart more. Bring the positive glass rod near the negative electroscope and the leaves collapse.
3. Bring the 100W light bulb within a few centimeters of the scope (don't touch). Turn on the bulb. The scope remains charged showing that IR and visible light do not deliver enough energy to eject the excess electrons even though the light is very bright!
4. Repeat using the UV light source near the top of the electroscope and immediately the scope discharges as electrons are emitted. This indicates the energy of the UV light is related directly to the frequency of the light since UV has a much higher frequency, even though it doesn't appear to be as bright to the human eye.
5. Recharge the Zn plate and electroscope negatively and bring the UV light near the electroscope but have the glass plate between the Zn and UV light. No e^- emission will result, showing the glass doesn't let the UV photons through. You can pull the glass away and the electroscope immediately discharges.
6. Repeat procedures 1-5 but use the Cu plate in place of the Zn. The same result will occur but not as good since the Cu has a higher work function and not as many electrons will be emitted. Zn has a work function of 4.3 eV and Cu has w = 4.7 eV.

Even though these are very close you will see a difference. Lead at 4.14 eV is another available material. Cesium is used in photoelectric apparatus since it has the low work function of 2.1 eV.



Topic 18: Activity/Demonstration 2 – Photons/Photoelectric Effect

Purpose:

To Observe:

(a) Photoelectric effect with a visual.
(b) Effect of different frequencies on photosensitive materials.
(c) Different materials have different work functions.

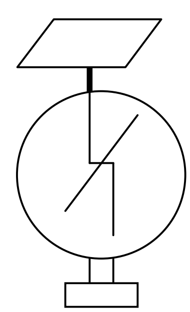
Materials:

Sensitive electroscope (Pasco or equivalent)
UV light source
100W incandescent bulb with socket
Glass sheet about five inches square
Zinc plate about three inches square
Copper plate about three inches square
Golf tube
Rabbit fur
Emery cloth
Match

Procedure/Questions:

1. Use the emery cloth to sand both sides of the zinc and copper to expose clean metal; wipe off with clean cloth.

2. Place the zinc sheet on the sanded top of the electroscope. (Pasco has different choices for a top.) See sketch.



3. Charge the golf tube with the fur and touch the tube to the zinc to charge the zinc and electroscope. Electrons are transferred to the electroscope.

4. Hold the 100W light bulb above the zinc and turn it on. What happens?

   (Even though the bulb is bright, the electroscope does not discharge.)

5. Now hold a UV light above the charged zinc/electroscope. What happens and why?

   (The electroscope begins to discharge immediately until it has no charge. This shows the photoelectric effect and that the UV photons have sufficient energy to eject electrons due to their higher frequency than the bulb.)

6. Why does the UV work and visible light does not?

   (The lower frequency, visible light is not enough to overcome the work function of the metal, although the metal will heat up from the IR radiation.)

7. Recharge the zinc/electroscope and hold the glass sheet above (not touching) the zinc. Shine the UV through the glass toward the zinc and see what happens.

   (The electroscope does not discharge since the glass absorbs the UV photons.)

8. Light a match and bring it near the charged zinc/electroscope. What happens?

   (The electroscope discharges, but for a different reason; the air is ionized and the free electrons on the electroscope combine with those ions causing the scope to discharge.)

9. Replace the zinc with copper and repeat steps #1-5. Compare to zinc.

   (Both zinc and copper discharge, but copper is harder since it has a higher work function.)

Topic 18: Activity/Demonstration – Photons/Photoelectric Effect

Purpose: To simulate "photon" properties in the context of the photoelectric effect.

Materials: 6 (or so) white plastic golf balls (electrons)
6 yellow plastic golf balls (electrons)
7 real golf balls (photons)
1 m ramp and support structure
1 metal pie tin – (the atom – having a potential well)
50 cm of string

Theory: This activity can be done as a demonstration or student activity to simulate how photons interact with matter in the photoelectric effect. Ideas to simulate follow:

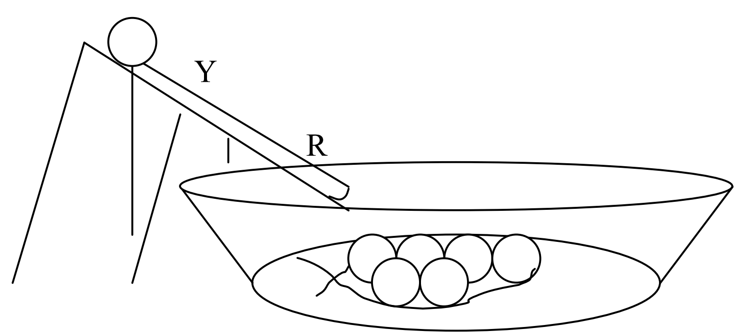
1. The energy of a photon is directly related to its frequency. $E \propto f$ $(E = hf)$

2. More "photons" striking a surface results in more stimulated "electrons"

3. There is no time delay for "electrons" to be ejected by incoming "photons"

4. Ejected electrons from an atom vary in velocity. Also, different materials have different "work functions."

Setup: Place the six (or so) white plastic golf balls into the pie tin into a single layer cluster held together with a loop of thread at their base. Set up a 1-m-long ramp at a small angle (maybe 10-20) that accommodates the rolling of the golf ball (photon) and aimed at the plastic golf balls (electrons).



A. Simulation of Photon Energy Related to Its Frequency

1. Experiment how far up the ramp the "photon" needs to be released so the "electrons" do NOT escape the "potential well" or jump the side of the pie tin. Mark that point as "R." This represents a RED photon of insufficient energy (lower frequency) to emit an electron. Motion of the electrons can be observed to illustrate "heating" within the atom.

2. Release the photon higher up the ramp toward the six electrons so one, or so, electrons are “JUST” emitted from the atom. Mark that spot as “Y,” which is to simulate a higher energy photon, say yellow. This higher-frequency photon has more energy, thus is capable of kicking out an electron.

3. Release the photon closer to the top of the ramp to simulate a more energetic photon of even greater frequency, like “blue.” Label that release location point “B.”

   Question:
   How does the “photon” frequency/energy affect the ejected electron’s energy and thus velocity? ($KE = ½ mv^2$)

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B. Simulation of Photon Intensity and Number of Electrons Ejected

1. Again place the six plastic golf balls as a cluster on the pie tin and the yellow photon at “Y” on the ramp. Release and observe.

   How many “electrons” are ejected with this more energetic photon?

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2. Now regroup the plastic golf balls and release the “more intense beam of photons” (use two golf balls) at the “Y” location on the ramp. This represents the same yellow photons, but more of them.

   How many electrons are now ejected compared to the single yellow photon collision? Explain what this illustrates?

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C. Simulation of Time Delay of Emission

Release one yellow or blue photon at Y or B to hit ONE “electron” head on.

Does the ejection of the electron seem "delayed" or "instantaneous"?

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D. Simulation of Work Function

1. Cluster the six yellow plastic golf balls on the pie tin. Now cluster six white plastic golf balls as a top layer on the yellow balls (two layers). Roll one "blue photon" down the ramp from "B." Count how many white and yellow electrons were ejected.

   (a) How many ''white" electrons and "yellow" electrons were ejected?

   W = ___________________ Y = ____________________

   (b) Give the reason for this outcome.

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2. Place six real golf balls in the pie tin in the cluster and roll one "blue" photon down the ramp.

   (a) What happened?

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   (b) Why? (Hint: What are the real golf balls simulating?)

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Topic 18: Photon/Photoelectric Effect Answer Sheet

$hf = W + \frac{1}{2} mv^2$

(Photon energy equals energy to free outer electrons called the work function plus the excess kinetic energy of the ejected electron.)

A. 3. The "yellow" photon has more energy (higher frequency); therefore the "electrons" are ejected at greater energy as viewed by the fast velocity of the ejected electron. The excess kinetic energy is just equal to $\frac{1}{2} mv^2$.

B. 1. The number of ejected "electrons" will vary, but the point is that these "yellow" photons have enough energy to eject the electron.

2. The two photons will kick out more electrons than one photon showing that "light intensity" will directly affect the output "current."

C. Instantaneous—little or no time delay as for the "real effect"

D. 1. (a) W = more than yellow   Y = less than white

(b) The "electrons" closer to the surface of the material are not bound as tightly and come out easier. The energy to remove these electrons is the work function.

2. (a) None or some electrons come out, but the number will be less than the plastic golf balls because this is a new material that has a higher work function.

(b) This new material simulates a different work function (electrons more tightly bound).