Lesson 33: Photoelectric Effect

Hertz Experiment

Heinrich Hertz was doing experiments in 1887 to test some of Maxwell's theories of EMR.

- One of the experiments involved using a coil of wire as a receiver to detect EMR produced by a separate device.
  - This was very much like Maxwell's own experiments with low frequency AC radiation.
- Hertz was having problems seeing the spark that was made by the coil, so he placed the whole thing inside a dark box and looked through a glass window.
  - Funny thing was, the sparks seemed shorter now. He could see them in the dark, but they just weren't as big anymore.
- Hertz noticed that when he changed the glass window to one made out of quartz, the sparks got bigger.
  - The big difference is that the glass blocks UV, but the quartz does not.
- In the end, Hertz concluded that if random UV radiation in the room was able to go into the box (it could only do that if glass did not block it) it would hit the coil and help electrons pop off making bigger sparks.
- Hertz did not try to figure out why this was happening.

Einstein's Explanation

Threshold Frequency

Einstein figured out that it was the frequency of the light hitting the metal that was important.

- When the UV light hit the metal of the coil, it had enough energy to knock off electrons.
  - This was happening because the individual photons of UV had enough energy according to the formula $E = hf$.
- If the metal is exposed to radiation with a frequency less than UV, nothing happened.
  - Since the frequency of the light is so low, each photon does not have enough energy to knock off the electrons.
- This critical minimum frequency that is needed to start knocking off the electrons was named the **threshold frequency**.
  - The special symbol used for it in formulas is $\mathbf{f_o}$.

Work Function

Einstein believed that to give a single electron the energy to move, the metal was hit by a single photon (destroying itself), and transferred its energy to the one electron.

- Since the electron is originally attached to the metal, some minimum amount of energy must be needed just to snap it off. Otherwise, electrons would just be dropping off of atoms all the time.
- Einstein called this the **work function** of the metal, since you needed to do work on the electron to break it off.
  - Every metal has its own work function, since different metals hold on to their electrons with different strengths.
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- Popping the electrons off starts to happen at a minimum threshold frequency, so that must correspond to the work function.
    - The formula for this is a modification of Planck's formula.

$$E = hf$$
$$W = h f_o$$

W = work function (J)
h = Planck's Constant
f_o = threshold frequency (Hz)

Warning!
Ok, sure, this formula is almost exactly the same as Planck's. The difference here is what we're talking about. Planck's formula is about any photon of EMR. The formula for work function is all about minimum energy needed to knock electrons off a metal. You must use the work function formula when calculating things concerning electrons being knocked off to show that you understand we are not just talking about the photons themselves.

- Just like Planck's formula, you can use the value for Planck's constant in electron volts and get your final answer in electron volts.
    - In fact, it is very common to give the value for the work function in electron volts.
- You could also use a maximum threshold *wavelength* instead of the minimum threshold *frequency*.

Example 1: **Determine** the threshold frequency of a material with a work function of 10eV.
Since the value for the work function is given in electron volts, we might as well use the value for Planck's constant that is in eV·s.

$$W = hf_o$$
$$f_o = \frac{W}{h}$$
$$f_o = \frac{10}{4.14\text{e-}15}$$
$$f_o = 2.41546\text{e}15 = 2.4\text{e}15\ Hz$$

Example 2: **Determine** the work function of a metal in Joules if the maximum threshold wavelength is 1.10e-7 m.

$$W = hf_o$$
$$W = \frac{hc}{\lambda_o}$$
$$W = \frac{6.63\text{e-}34(3.00\text{e}8)}{1.10\text{e-}7}$$
$$W = 1.80818\text{e-}18 = 1.81\text{e-}18 J$$

Remember that c = f λ so we can change the formula just like we did for Planck's formula.

Millikan's Measurements of the Photoelectric Effect

Robert Millikan set up an experiment using the following apparatus.

A **UV light source** was aimed at a **piece of zinc** inside a **vacuum tube**.

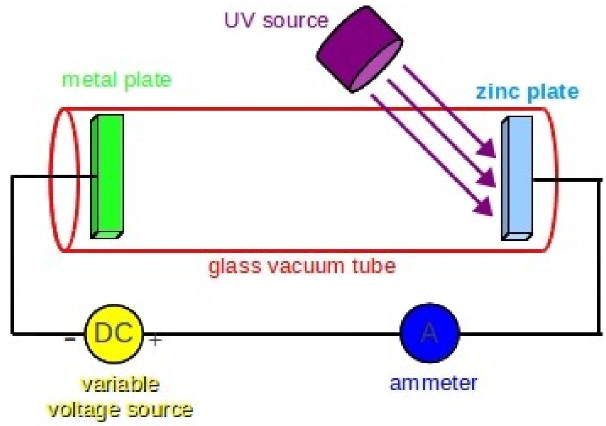

Illustration 1: Photoelectric Effect apparatus

- With the **UV source** turned on a current was shown on the ammeter.
  - How could a current flow when there is a huge gap between the wires in the **tube**?
  - It was reasoned that when the **UV light** hit the **zinc plate**, the photons of **UV** knocked electrons off the **zinc**. These electrons fly across the **tube** and hit the **metal plate**.
  - The result is a negative charge on the **metal plate** (it's gaining electrons) and a positive charge on the **zinc plate** (it lost the electrons).
  - Current flows in the wire, as the electrons move from the **metal plate** back to the **zinc plate**.

Stopping Voltage

To further test these ideas we can turn on the variable voltage source.

- Notice that the variable voltage source is set up so that the metal plate will be negative and the zinc plate becomes positive.
- This voltage should work *against* the electrons getting all the way from the zinc plate to the metal plate. Only electrons with enough kinetic energy (going fast enough) will be able to get to the metal plate.
  - Any electrons that have too little energy will just get pushed back by the negatively charged metal plate and stick back onto the zinc plate.
- The voltage was slowly increased from zero, and for a while nothing appeared to be changing. But, there came a point when the voltage became too great for even the fastest moving electrons to get across the gap. At this point (and for any higher voltages) the ammeter gives a reading of zero.
  - This is the stopping voltage, the voltage that is enough to get rid of all the kinetic energy the electrons had trying to get across the tube.
- We can come up with a formula for this by relating it to the ideas we have from Lesson 13...

$$V=\frac{\Delta E}{q}$$

$$\Delta E=qV$$

$$E_{k\ max}=qV_{stop}$$

$E_{k\ max}$ = kinetic energy of fastest moving electrons (J)
q = charge of an electron (C)
V_{stop} = the voltage needed to stop electrons (V)

Example 3: **Determine** the maximum kinetic energy of electrons emitted from a zinc surface if they are stopped by a 16 N/C uniform electric field over a distance of 3.0cm.

First calculate the voltage.

$$|\vec{E}| = \frac{\Delta V}{\Delta d}$$

$$\Delta V = |\vec{E}| \Delta d$$

$$\Delta V = 16(0.030)$$

$$\Delta V = 0.48\,V$$

Then figure out the maximum kinetic energy of the fastest moving electrons.

$$E_{k\,max} = q V_{stop}$$

$$E_{k\,max} = 1.60\text{e-}19(0.48)$$

$$E_{k\,max} = 7.68\text{e-}20 = 7.7\text{e-}20\,J$$

Photoelectric Effect Formula (the Biggy!)

If the frequency of the incoming light is great enough, there should be enough energy to break off the electron *and* have some left over to give it some kinetic energy. So…

$$hf = W + E_{k\,max}$$

Input Energy
This is the energy of the incoming photon.

Work Function
This is the energy that is needed to snap off the electron.

Maximum Kinetic Energy
This is the part of the energy that allows the electron to move.

This is really a formula that shows ***conservation of energy***.

- The original **input energy** is from the incoming photon.
- Some of this energy is used to just snap off the electron from the metal. This is the **work function**.
- Any left over energy becomes **kinetic energy** used by the electron to go zipping across the tube.

Note, some electrons will need more than the bare minimum W to be released (they might be attracted more strongly), so their E_k is not as great as the maximum. That's ok, though, since we'll only worry about the electrons that came off the easiest and have the maximum kinetic energy.

This formula is built from separate formulas on your data sheet.

- From the way that we've seen that each of those individual parts can be changed around, we can adjust this basic formula to fit a particular problem as necessary.

Example 4: The threshold frequency of silver is 1.14e15 Hz. EMR with a wavelength of 2.50e-7 m strikes a piece of pure silver. **Determine** the speed of the electrons that are emitted.

First we'll figure out how much kinetic energy the electrons are getting. We will have to substitute formulas into the one we've built so far.

$$hf = W + E_{k\ max}$$

$$\frac{hc}{\lambda} = hf_o + E_{k\ max}$$

$$E_{k\ max} = \frac{hc}{\lambda} - hf_o$$

$$E_{k\ max} = \frac{6.63\text{e-}34(3.00\text{e}8)}{2.50\text{e-}7} - 6.63\text{e-}34(1.14\text{e}15)$$

$$E_{k\ max} = 3.978\text{e-}20 = 3.98\text{e-}20\ J$$

Now figure out the velocity of the electron.

$$E_{k\ max} = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E_{k\ max}}{m}}$$

$$v = \sqrt{\frac{2(3.98\text{e-}20)}{9.11\text{e-}31}}$$

$$v = 295521 = 2.96\text{e}5\ m/s$$

Homework

p716 #1-3
p718 #1-2
p719 #1-3
p720 #2, 6, 7