Section 4: Photoelectric Effect

- Explain qualitatively and apply the formula for the photoelectric effect.
- State and solve problems using Planck’s equation (E = hf)
- Define and calculate the stopping potential
- Convert Joules (J) to electronvolts (eV) and vice versa
- Define and calculate the work function
- Relate the energy of the incident light (photon) to the work function
- Explain how scientific knowledge evolves as new evidence comes to light and as laws are tested and subsequently restricted, revised or replaced.
- Analyze and describe examples where technological solutions were developed based on scientific understanding
- Analyze technological systems to interpret and explain their structure.
When light shines on a metal surface, the surface emits electrons. This phenomenon is known as the **photoelectric effect**. However, only certain frequencies worked. Making the light more intense (ie. brighter) **should** have worked according to classical wave theory, but it did not.

**NOTE**: This appears to support the particle nature of light. Since we view electrons as particles, the light coming in can be understood as tiny cue balls that are bumping out the billiard balls (the electrons).

**Photoelectric Effect Facts**

- For a given frequency of light, the kinetic energy of the electrons ejected from a metal surface was the same.
- Increasing the brightness of the light (increasing the amplitude) caused more electrons to be ejected; their individual energies remained the same.
- The energy of the emitted electrons was directly related to the frequency of the light striking the surface. (If the frequency of incident light is increased, the wavelength of the light will decrease and the kinetic energy of the ejected electrons will increase.)
Contradictions between the Photoelectric Effect and Wave Theory

This effect completely contradicted the wave theory of light: that is, the energy of in a wave is a function of its amplitude. Increasing the amplitude or brightness, should increase the energy of the ejected electrons. However this was not the case. Einstein decided to undertake an explanation of the photoelectric effect from a theoretical point of view using Plank’s quantum idea.
Einstein’s Work on the Photoelectric Effect

Albert Einstein explained the photoelectric effect based on Planck’s quantum idea. For this work, he received a Nobel Prize in physics in 1921.

Einstein proposed that the photoelectric effect be a test of Planck’s quantum hypothesis (i.e. that $E = hf$, or that the energy of a photon of light is directly proportional to its frequency).

Einstein describes light as being many up of particles of energy called photons. The quantum (or photon) theory of light predicts that each photon of incident light on a metal surface can strike an electron in the material and eject it if the photon has enough energy to do so. The maximum energy of the ejected electrons is then related to the frequency of the incident light.

In other words, individual photons of light have definite quantized amounts of energy ($E \propto f$). If the individual photons of light lack enough energy then no effect is noticed. If an individual photon has enough energy then a photo-electron will be released. From this point on, more incident photons (i.e. brighter light) will release more photo-electrons (higher current). Below this threshold frequency, no amount of photons of light will work.
http://phet.colorado.edu/en/simulation/photoelectric

http://www.youtube.com/watch?v=ubkNGwu_66s

http://www.youtube.com/watch?v=jAt4Liq3bgc
The Apparatus

When light hits the negative metal plate electrons are bounced out of the plate. This is called the photoelectric effect.

The photoelectric effect apparatus consisted of a shiny metal surface enclosed in a vacuum tube to prevent oxidation. When light was shone on the metal surface, some electrons were ejected from it. The metal being struck by the light was negative (the cathode) and the terminal collecting the electrons was made positive (the anode), so the electrons zipped from one terminal to the other as soon as they were liberated by the photons of light.

The electrons streamed across to the collector plate because the voltage source in the external circuit made the collector plate positive. The anode and cathode were connected via a power supply providing a potential, and an ammeter that measured the amount of current.

Then the potential was reversed so that the anode became negatively charged, causing electrons to be repulsed from the anode. If the voltage (or potential) is increased (that is, if the collector plate is made more negative) the electrons will finally stop coming across.
Note: The liberated electrons have kinetic energy while they are moving and potential energy when they are forced to stop. (Think of a rock that is thrown into the air and brought to a stop by gravity.)

According to the law of conservation of energy, the kinetic energy that has "disappeared" and the potential energy that has taken its place are equal!

So, the maximum kinetic energy of the ejected electrons ($E_{k\text{Max}}$) is equal to the electric potential energy required to prevent electrons from being ejected from metal surface. This potential energy is called the stopping potential, $V_{\text{stop}}$.

Recall: Electric Potential Energy is given by

\[ E = qV \]

For an electron $q = e – \text{the elementary charge}$

So, $E = eV$

In the case of the photoelectric effect, $V = V_{\text{Stop}}$

\[ E = eV_{\text{Stop}} \]

In other words, the electric potential energy of an electron that has just been stopped is $E = eV_{\text{stop}}$ and this is equal to the kinetic energy that the electron use to have.

In equation form: $E_{k\text{ max}} = eV_{\text{stop}}$
Einstein applies Planck's Quantum Idea to Photoelectricity

- The photoelectric effect occurs when light strike a metal and electrons are ejected.
- This does not happen for just any old light.
- It will not happen for red light. Increasing the brightness (increasing the amplitude) of the red light will still not eject the electrons.
- So, contrary to what the wave theory would predict, the amplitude is not an indication of the amount of energy that the light can give up to the electrons in the metal plate.

The pictures to the right show three different brightness of blue light.
- Even the faintest blue light knocks electrons from the metal plate.
- As the light becomes brighter (greater amplitude), more and more electrons are emitted.
There are some conclusions to be drawn from the above observations:

- Since even the bright red light did not have enough energy to dislodge the electrons, but the faint blue light did, it must be that the energy of the incoming light is governed by the frequency of the light and not by the amplitude of the wave (blue light has a higher frequency than red light).

- If the light has high enough frequency to cause the photoelectric effect, then the brighter the light the more electrons knocked out of the metal.

- Since making the impinging blue light brighter increases the number of electrons, the number of photons in the light must govern the light's brightness. The brighter the light, the more the photons, and each photon knocks out one electron.

- If the frequency of the photons is not large enough to dislodge electrons, it makes no difference how many photons there are. That's why even bright red light does not cause a photoelectric effect.

- The photoelectric effect provides very good evidence that light is composed of tiny packets/bundles/quanta of energy. (Radiant energy was transmitted in bundles or quanta, each with a specific energy.)
A graph may help to sum up the above statements. The photocurrent graph below results from light of two different intensities \((Int)_1\) and \((Int)_2\) being shone on the same material. \((Int)_2 > (Int)_1\).

1. If the frequency of the impinging light is less than \(f_o\), \((\text{cut-off or threshold frequency})\) then no electrons will be liberated. When \(f = f_o\), the electrons are just barely liberated.

2. Once the threshold frequency has been exceeded, the \textbf{current} jumps to a maximum value which \textbf{depends on the intensity (i.e. brightness)}. The greater the intensity, the greater the number of incoming photons, and the greater the number of ejected electrons which means the greater the current. But for each light intensity the current will be constant as illustrated by the \textbf{horizontal lines} of the graph.

3. For a particular intensity, the \textbf{size of the current does not depend on the frequency of the incoming photons}. This is illustrated by the horizontal parts as frequency increases on the x-axis. So, \textbf{increasing the frequency} does not increase the size of the current, but it \textbf{does increase the energy of each emitted electron}.

\textbf{The Work Function}

The dislodging of electrons is similar to kicking a soccer ball that is stuck in sand. Your in-coming foot has energy which must be split into two pieces: one bit does work to loosen the ball from the sand while the remaining energy moves the ball on its way (gives it some maximum amount of kinetic energy).

The energy provided from an incoming photon \((E_\gamma = hf)\) serves two functions:

- The first is that it does work to free electrons. This aspect of the energy is referred to as the work function, \(W_o\).
- The remaining energy of the photon provides the freed electron with kinetic energy \(E_{k\text{max}}\). 
So, the Energy of the incoming photon is equal to the work function plus the kinetic energy of the electron

\[ E_\gamma = hf = W_0 + E_{K\text{max}} \]

or

\[ \frac{(hc)}{\lambda} = E_{k\text{max}} + W_0 \]

The **maximum amount of kinetic energy** of the emitted electron is always **less than the energy of the impinging photon** because some of the photon energy is used up to liberate the electron from the metal.

\[ E_{k\text{max}} = hf - W_0 \]

or

\[ E_{K\text{max}} = E_{\text{photon}} - W_0 \]

The work required to liberate each electron is \( W_0 \) and Einstein gave it the name **work function**.

**The Stopping Potential Revisited**

Recall that the stopping potential was that applied reverse potential that prevented the electrons from reaching the collector plate. For each electron with charge \( e \), the stopping potential gives each electron an electric potential energy, \( E = eV_{\text{stop}} \),

and that potential energy is just equal to the kinetic energy lost by the electron

\[ E_{k\text{max}} = eV_{\text{stop}} \]

But

\[ E_{k\text{max}} = hf - W_0 \]

So,

\[ eV_{\text{stop}} = hf - W_0 \]
We will look more closely at

\[ E_{k_{\text{max}}} = eV_{\text{stop}} = hf - W_0 \]

- slope is \( h \)
- y-intercept is \(-W_0\).

The graph crosses the x-axis at \( E_k = 0 \) and frequency equal to a special frequency called \( f_0 \), the cut-off or threshold frequency. If the frequency of the impinging light is less than \( f_0 \), then no electrons will be liberated. In fact at \( f = f_0 \) the electrons are just barely liberated. All of the photon energy is used up in the work function \( (W_0) \) just to break them free and no energy is left over to give the electrons kinetic energy. You can see from the equation that when \( E_k = 0 \),

\[ hf = W_0 + \overrightarrow{E_{k_{\text{max}}}} \]

or

\[ W_0 = hf_0 \]
\[ \frac{hc}{\lambda} = W_0 \]

Therefore, in order for the photoelectric effect to occur, the energy of the incident photon must be greater than the work function: \( E_{\text{photon}} > W_0 \).
Relationship between Incident Photon Energy and Work Function

1. If \( E_\gamma = hf = \frac{hc}{\lambda} < W_o \), then no electrons are emitted.

2. If \( E_\gamma = hf = \frac{hc}{\lambda} = W_o \), electrons are not ejected (or just barely liberated)

3. If \( E_\gamma = hf = \frac{hc}{\lambda} > W_o \), then electrons are ejected.
Examples

1. A certain metal with a known work function of 2.8 eV is shone with light of wavelength 625 nm. Will the photoelectric phenomenon be observed?

The photoelectric phenomenon will be observed only if the incoming photons have enough energy to free the electrons from the surface of the metal. That is, $E_{\text{photon}}$ must be at least equal to the work function $W_0$.

\[
h_f = W_0 + E_{\text{max}}
\]

\[
W_0 = 2.8 \text{ eV}
\]

\[
\lambda = 625 \text{ nm}
\]

\[
E_{\gamma} = \frac{hc}{\lambda}
\]

\[
= \frac{6.626 \times 10^{-34} \text{ J s}}{625 \times 10^{-9} \text{ m}}
\]

\[
= 3.18 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.602 \times 10^{-19} \text{ J}}
\]

\[
= 2.0 \text{ eV}
\]

Since $E_{\gamma} < W_0$, no electrons will be ejected. 

\[\text{Photoelectric effect will not occur.}\]