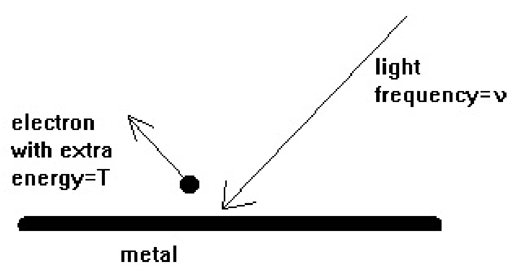
Chapter 34: Photons

The Photoelectric Effect

We have spent the last two chapters convincing you that light is actually a wave, and you may recall from the small historical presentation given earlier that after the work of Maxwell, Hertz, Michaelson and Morley, the matter seemed settled. However, one very disturbing problem still remained. It was called the photoelectric effect.

It was discovered, before the turn of the century, that if light was shined on a piece of metal, electrons would fly off. According the wave theory of light, this makes sense. What was happening was that the light energy of the wave gave the electrons enough energy to "break away" from the electrical attraction of the nucleus. In technical terms, the light was providing the ionization energy to the electrons. If the light provides an amount of energy higher than the ionization energy, then the electrons not only escape the nucleus, but are found flying around with extra kinetic energy. However, when we look at the results of the photoelectric effect in experiments, some surprising things come to light. First let us make some predictions using the wave theory of light and logic. Imagine shining a light on the metal below:



Logic tells us to expect the following results:

- The more intense the light, the more electrons emitted.
- The extra energy of the electrons, T, should depend on the intensity of the light used. In other words, brighter light should give off higher energy electrons.
- Any wavelength of light can be used to free the electrons, provided it is bright enough.

While the first of these conclusions turned out to be correct, the other two are contradicted by experiment. In fact, the following two results were found:

- The extra energy of the electrons is related to the wavelength of the light, not the intensity.
- There is a cutoff wavelength, λ_c, above which no electrons are emitted, regardless of the brightness of the light.

Take special notice to how these two results are in direct contradiction to the wave theory of light. If light were a wave, we should be able to produce one with sufficient energy at any wavelength to knock out the electrons. Furthermore, the wavelength should have nothing to do with the extra energy, it should depend on the intensity.

Albert Einstein, in 1905, proposed an explanation. He stated that light was actually a series of little balls of energy called photons. Each photon carries a set amount of energy based on the frequency of the light. Brighter light means more photons, not different ones. If light was indeed made up of photons, the photoelectric effect could be explained. Imagine the effect as occurring between one electron in an atom being bombarded by billions of photons. If the photon had enough energy (dependent on wavelength) then it could free the electron. If it didn't (the wavelength was too long) then no matter how many photons were thrown, the electron would never get enough energy to break free (an assumption made here is that only one photon at a time can react with any given electron). Furthermore, since the energy depends on the wavelength, the extra energy of the electron after it is freed would depend on the wavelength and not on the intensity (the number of photons thrown). One other result of the experiment fits both the wave theory and the photon theory; the brighter the light, the more electrons that are freed. There was one other result that contradicted the wave theory, and that is that if light were wave, it should take a few seconds for the waves to deliver enough energy to knock out an electron. In experiments, the electrons were released within a nanosecond.

Einstein went on to suggest that the energy of one particular photon is given by the equation:

$$E = h\nu$$

Where h is called Plank's constant and has a value of 6.63×10^{-34} J.s (or 4.14×10^{-15} eV.s). He also stated that photons can carry momentum ($p = E/c$) and that they have no mass. All of these predictions have been supported by experimental evidence since that time and are accepted today.

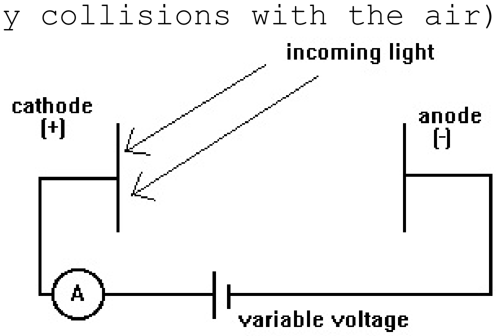
EX. JKIU:) What is the energy (in both units) and momentum of a photon of visible light (use 650 nm)?

As an interesting side note, most chemical reactions require about this much activation energy, most notably photosynthesis. If the reactions required much greater energy or much less, visible light would not cause them to react. It is a wonderful coincidence (?) that this is so, because this is the type of light that most plentifully reaches us from the sun. Without this coincidence, life would either not be possible or be severely limited on earth.

EX. RVJU:) How many photons are given off by a 60 W light bulb operating at 500 nm in one second? Assume the 60 W applies to light output, not electrical usage as it actually does.

EX. OUN:) It is possible to create a laser powerful enough to suspend a glass bead in its beam. Since each photon carries momentum, its collision with the bead could impart enough force to keep the bead suspended. What wattage of laser would be required to suspend a 0.01 g bead in its beam of 650 nm light?

With this new knowledge of the nature of light, let us return our attention to the photoelectric experiment itself. Our previous discussion explained the experiment in very conceptual terms, but for an experiment which carried such an incredible conclusion, it behooves us to look at exactly how it was carried out in detail. The device consisted of an anode (negative terminal) and a cathode (positive terminal) as shown below (actually, the cathode and anode are set together inside a vacuum tube so that the electrons are not impeded by collisions with the air).



Imagine for an instant that the variable voltage was set at zero. In this case, electrons would come off the cathode (made of metal) and reach the anode. This would create an electrical current that would be measured by the ammeter. In this case, the extra energy of the electrons would be:

$$T = h\nu - W$$

Where W is what is called the work function and represents how strongly the electrons are held to the metal. It is similar to the ionization energy, but not the same since some electrons further in the metal must be harder to release than the surface electrons. The work function is different for different metals.

The variable voltage is then increased and this works against the motion of the electrons. As the voltage goes up, the current in the ammeter should go down, since electrons will find it harder and harder to complete their journey. At some point, the voltage from the variable source will completely stop the electrons and at this time we know that the extra energy of the electrons equals the voltage time the charge, or:

$$T = eV$$

or

$$eV = h\nu - W.$$

At some point, as was explained before, if the frequency is too low, there will be no electrons knocked off the metal. In this case, at the cutoff, we have:

$$0 = h\nu - W$$

$$W = h\nu_{cutoff}$$

Any frequency below the cutoff frequency will not cause electrons to be knocked off, regardless of how intense the light becomes.

EX. IJUHY:) The work function for copper is 4.70 eV. Determine the cutoff wavelength for copper and determine the amount of extra kinetic energy electrons will possess if a light of 120 nm is used. Also determine the stopping potential.

A second Nobel Prize in Physics was awarded for work on the photoelectric effect to Robert Millikan, who used this effect to precisely measure Plank's constant (which, by the way, is a tremendously important constant in many different areas of modern physics, it is not regulated to just this effect). This was the same Millikan who first accurately determined the elementary charge.

Wave of Particle?

At this point, the student might be a little confused, since we spent a long time describing light at a wave and now we just stated that light is a particle. So which is it? The answer is both and neither (there, that should clear up the confusion). Today we say that light is both and wave and a particle, depending on the circumstances. In reality, light is probably neither, but in some situations it is best described as a wave and in other it is best described as a particle. The wavelike aspects of like become more and more apparent as the wavelength grows and the particle like aspects become more apparent as the wavelength shrinks. We say that longer light behaves more like waves, thus it is rare to discuss photons of radio waves and short light behaves like particles, thus x-rays and gamma rays are almost exclusively treated as photons.

Another interesting aspect of this "wave/particle duality" is that with only a few minor exceptions, most experiments can be explained with either description. The two best examples are diffraction patterns and polarization. In the previous chapters we said that these were strong proof for light being a wave. However, when dealing with photons, you must use the laws of quantum mechanics, which rely heavily on probabilities. It turns out, if you do all the necessary and ugly calculations, that in the case of double slit diffraction, you will actually have alternating areas of high and low probability for a photon striking an area on the screen. In short, the dots seen on the screen exactly match the probability patterns for where photons would land if they were shot out of two small openings. Polarization reaches the same conclusion. The exact percentage of intensity that gets through the polarizer is equal to the probability of a photon passing through. In other words, a polarizer at a 45° angle we would expect to allow 50% ($\cos^2 45°$) of the intensity through. In such a case, a single photon would have a 50% chance of getting through the material. Thus when large numbers of photons are propelled at the material, 50% of them make their way through.

To conclude this short, but very important chapter, we are presented with an interesting philosophical conclusion. If we design our experiment to look for light to be a wave, we will see the results of our experiments as such. If we design our experiment to look for it to be a particle, our results will show us that it is. It seems that the actual experiment predetermines the outcome. This is not coincidence. Modern physics tells us that a law of nature seems to be: "You find what you look for."

Assignment #34

1.) (A.) Which is more energetic, blue light or red light? (B.) What are the approximate energies of a photon of each one?

2.) Assume that a 100 W light bulb gives off all of its energy in the form of visible light, with an average wavelength of 550 nm. How many photons per second strike 20 cm x 30 cm piece of paper located 1 meter from the light bulb ? (L15)

3.) If an x-ray photon has an energy of 10 KeV and a gamma ray has an energy of 1.0 MeV, what wavelengths are associated with each? (L16)

4.) What is the range of energies of photons of visible light with wavelengths of 350 to 700 nm ?(L17)

5.) Find the cutoff frequency for silver (W = 4.73 eV). If you wished to liberate electrons with an average extra energy of 3 eV, what wavelength of light would you need to shine on the metal.

6.) The work function for tungsten is 4.52 eV. Explain precisely what would happen if you shined light of 300 nm on the metal and why.

7.) What stopping potential would be needed if light of 200 nm was shined on zinc (work function = 4.31 eV).

8.) Imagine that you did a photoelectric experiment and found the following data. By graphing the data, determine a value of h, find the work function of the material and explain how this graph supports the photon hypothesis and not the wave theory. You may use an accepted value for the electron charge.

Radiation Frequency	Stopping Voltage
1.12×10^{15} Hz	0.5 V
1.24×10^{15} Hz	1.0 V
1.31×10^{15} Hz	1.3 V
1.43×10^{15} Hz	1.8 V
1.63×10^{15} Hz	2.6 V
1.73×10^{15} Hz	3.0 V