Unit 5 Modern Physics

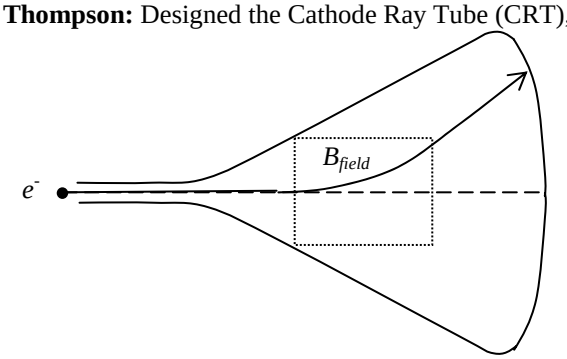
5–27 Atoms, Energy Levels, and Photoelectric Effect

Electromagnetic Radiation: In the previous review sheet we discussed the electromagnetic spectrum.

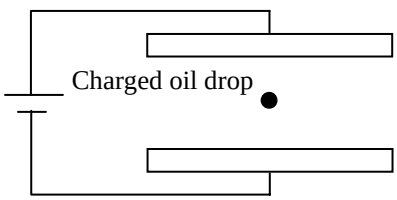
Maxwell: Derived a famous series of four equations that could completely describe electromagnetic effects. His equations, which were a compilation of the work of many other famous scientists, showed the existence and predicted the speed of these waves. However, you won't need the equations now. You can enjoy this chapter of physics in college.

Atomic Theory

Thompson: Designed the Cathode Ray Tube (CRT), the basis for TV and computer monitors. In the partially evacuated tube he had two electrical terminals, thus creating an electric field. When a potential difference was created between the electrodes (plates) he witnessed an eerie beam that came from the negative (cathode) plate and went to the positive plate. Creating a hole in the positive plate allowed the beam to pass through and strike the end of the tube. He surmised the existence of negative particles that must have come from inside the atom. The stream of particles could also be bent by an intervening magnetic or electric field. The atom was no longer recognized as the smallest entity in the universe. The particles making up the beam were called electrons.



Milikan Oil Drop: He charged oil drops with the newly discovered negative particles. He then sprayed the oil drops between two charged plates. He could adjust the potential difference between the plates until the oil drops were suspended in mid air. This means that the force up = the force down. So the electric force up = the gravity force down. $Eq = mg$ so



$\boxed{q = \frac{mg}{E}}$ By finding the mass of the oil drop and noting the strength of the electric field he could calculate the excess charge on the oil drop. He performed the experiment many times. He noted that the charge was always a multiple of 1.6×10^{-19} C and he never found a value smaller than this. So he concluded that this is the charge on the electron. After all charge comes in quanta, or whole number quantities. There are no half electrons.

Rutherford: Fired alpha particles at gold foil. Around the foil he placed a screen sensitive to alpha particles. He thought the heavy and fast alpha particle would fire right through the foil. While most did, he did note that many rebounded from the foil. He likened this to shooting a cannon at tissue paper and having the shell bounce back. He postulated that the atom was mainly empty space, but that there was a small dense nucleus comprised of positive particles (protons) located at the center. The empty space would account for most alpha particles passing through. The positive nucleus would explain how the positive alpha particles were bounced back. He did calculations based on the various trajectories of the alpha particles, and he was able to predict the relatively small size of the nucleus. His model of the atom was similar to the solar system (planetary model) with the nucleus (sun) at the center and the electrons (planets) orbiting at a great distance.

Einstein: Postulated that light has a particle nature, and travels in packets of energy known as photons.

Planck: Found the energy of a photon. $\boxed{E = hf}$. The energy of a photon is Planck's constant (h) x frequency.

Emission Spectrum: It was noted that when gaseous elements were placed in a tube at near vacuum and a potential difference was placed at the ends of the tube (Thompson *CRT*) different colors were seen. When shot through a diffraction grating the colors showed up as discrete lines with dark areas in between. Formulas were worked out for Hydrogen, the simplest element and the placement of the lines fit a mathematical pattern.

Bohr: He predicted that the atom was similar to Rutherford's model, but Bohr added the concept of energy levels. The fact that atoms only emitted certain frequencies of light implied that the electrons could only occupy certain discrete energy levels. And these electrons could never be in between these energy levels. When photons strike an atom, the electrons (normally in the ground state) of the atom absorb the energy. These electrons (excited) now have higher energy and thus move to higher energy levels within the atom. When the electrons returned to the ground state photons are emitted since the electrons loose energy. But the electrons may drop to a variety of levels on the way back to the ground state. This explains the many colored lines in the emission spectrum and the calculations matched those of the emission spectrum. The **Bohr Model of the atom** is outdated & incomplete, but it is still used to visualize the atom.

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Debroglie: Felt that since light can act as both a particle (photon) and a wave, perhaps electrons (a particle) can have a wave property as well. He calculated the wavelengths of electrons $\boxed{\lambda = h/p}$ and found that theoretically an electron in the lowest energy level has one electron wavelength in a ***standing matter wave***. An electron in the second energy level completes two wavelengths, etc. This resulted in the ***Wave Mechanical Model of the Atom***. So the electrons were not jumping from energy levels as Bohr had surmised, rather they were changing wavelength when bombarded by photons.

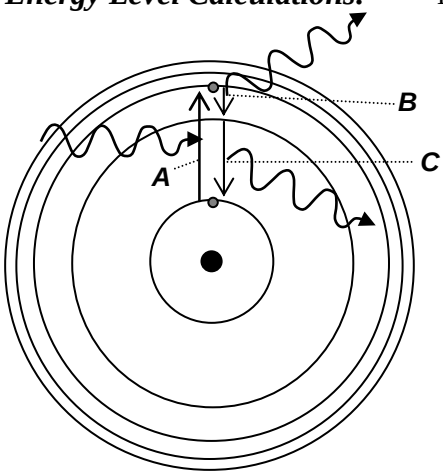
Heisenberg: Postulated that you can never know both the location and the momentum of an electron simultaneously. His ***Uncertainty Principle*** states that you cannot find an electron or predict what it will do, since if you shoot photons at electrons to see what their doing the photons interact with the electrons changing their location and / or their speed.

Schrodinger: Performed the calculations to narrow down the possible locations that electrons may be found in an atom. These statistical shells that electrons occupy are the basis of the current ***Electron Shell Model of the Atom***.

Einstein: Found the mass energy equivalence $\boxed{\Delta E = (\Delta m)c^2}$. Even though a photon is really mass-less energy it does have a mass equivalence. So if its energy can be converted to a mass value, then the photon can be given a mathematical momentum. So Planck's equation is updated. $\boxed{E = hf = pc}$

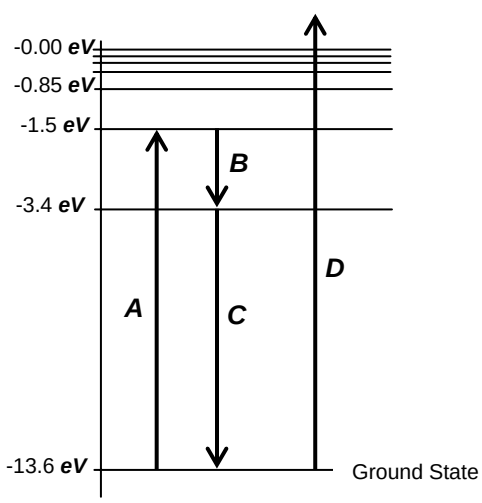
Energy Level Calculations:

Bohr's model has been updated, but the energy levels still hold mathematically.



If a photon of the right frequency and energy were to strike the lone electron in hydrogen while it is in the ground state, the electron would then acquire all of the photons energy. The ***photon is absorbed by the atom***. The energy of the photon determines how much energy the electron receives and thus determines the energy level that the electron is boosted to. Perhaps the electron would receive enough energy to be excited to the 3rd energy level as shown in process ***A***. This excited electron would be unstable and would eventually return to the ground state, but not necessarily in one leap. It could conceivably drop all the way back releasing a photon of the same frequency and energy as the one that struck the electron boosting it out of the ground state. Or it might drop to the 2nd energy level first (***B***), and then finally drop back to the 1st energy level (***C***). This two-step return will result in two photons that have different frequencies, and these photons are also different from the photon that hit the electron initially. ***Photons are emitted from the atom***. Here are some of the energy levels of a hydrogen atom. The atom is small, so energy is measured in electron volts.

Drawing a circular atom is tedious. The following covers the same scenario as detailed above, but includes the mathematical steps and an additional step ***D***. Remember this is only one scenario, there are many energy levels.



A: ***Absorption*** of a photon. The hydrogen atom is bombarded with light of frequency, 2.92x10^{15} *Hz*.

$$E = hf = \left(4.14\times10^{-15} eV\cdot s\right)\left(2.92\times10^{15} Hz\right) = 12.1 eV$$

As a result an electron in the ground state, -13.6 *eV* is boosted to the second energy level, -1.5 *eV*. In this case it drops to the first energy level and then drops back to the ground state. Lot's of possibilities exist.

B: ***Emission*** of a photon. The electron falls to the first energy level, a drop of 1.9 *eV*. This corresponds to a frequency of,

$$f = E/h = (1.9eV)\Big/\left(4.14\times10^{-15} eV\cdot s\right) = 4.59\times10^{14} Hz$$

A photon of light is emitted from the atom with this frequency. This ***generates a distinct band of light on the emission spectrum***.

C: ***Emission*** of a photon. Next the electron falls back to the ground state, a drop of 10.2 *eV*. This corresponds to a frequency of,

$$f = E/h = (10.2eV)\Big/\left(4.14\times10^{-15} eV\cdot s\right) = 2.46\times10^{15} Hz$$

A photon of light is emitted and this ***generates a distinct band of light on the emission spectrum***.

D: ***Ionization***. If a photon strikes a hydrogen atom electron in the ground state with more than 13.6 *eV* the electron receives enough energy to leave the atom entirely. The hydrogen atom lacking its electron becomes an ion. Therefore, this energy is referred to as the ***ionization energy***. (Also called the ***work function***. See below.)

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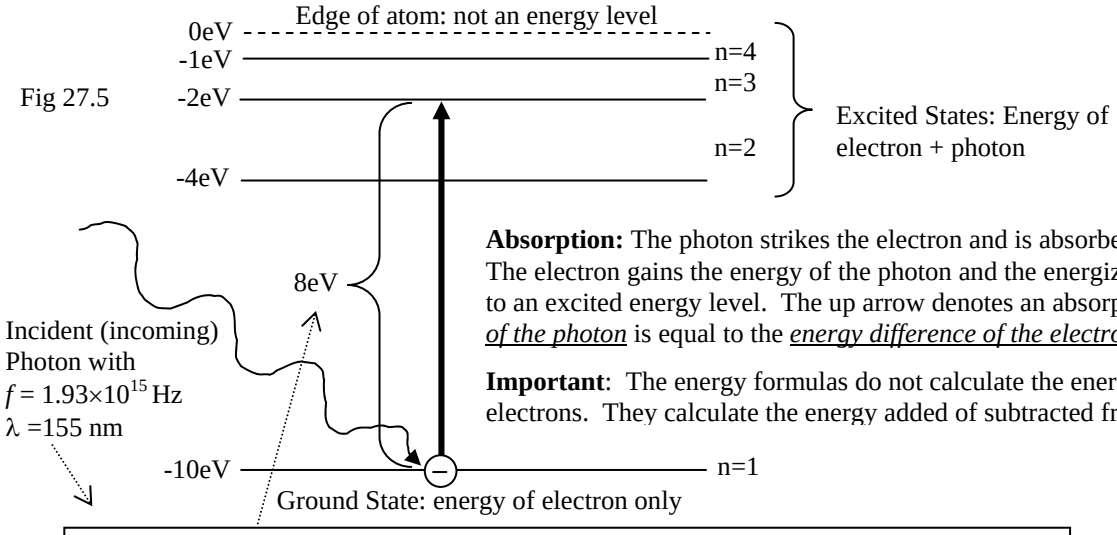
Example 27.1: Energy Levels: Absorptions

This hypothetical atom is struck by a photon, f = 1.93×10^{15}. Fig 27.5 details the flow of energy.

Fig 27.5



Absorption: The photon strikes the electron and is absorbed by the electron. The electron gains the energy of the photon and the energized electron moves to an excited energy level. The up arrow denotes an absorption. The *energy of the photon* is equal to the *energy difference of the electron*.

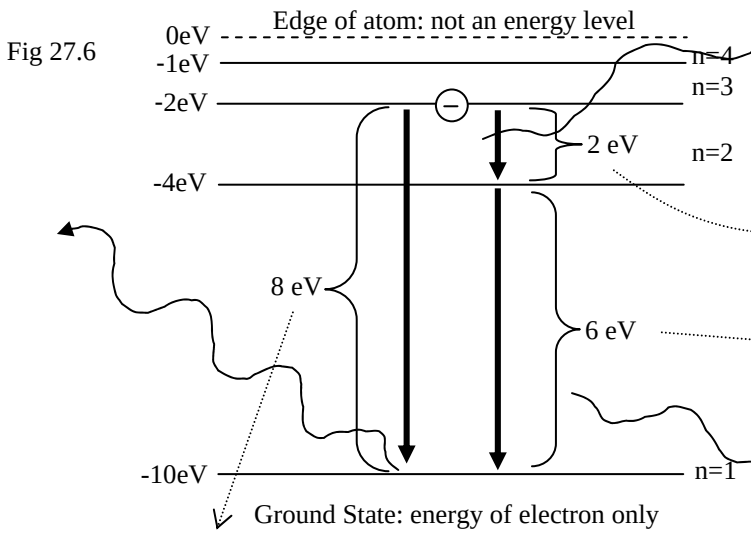
Important: The energy formulas do not calculate the energy levels of electrons. They calculate the energy added of subtracted from electrons.

$$E = hf = \left(4.14\times10^{-15}\right)\left(1.93\times10^{15}\right) = \boxed{8eV} \quad and \quad E = \frac{hc}{\lambda} = \frac{(1240)}{(155)} = \boxed{8eV}$$

Example 27.1: Energy Levels: Emissions

This same atom is eventually looses this extra energy. Fig 27.6 details all the possible energy transitions.

Fig 27.6



$$f = \frac{E}{h} = \frac{(2eV)}{\left(4.14\times10^{-15}\right)} = \boxed{4.83\times10^{14}\,Hz}$$

$$\lambda = \frac{hc}{E} = \frac{(1240)}{(2eV)} = \boxed{620nm}$$

$$f = \frac{E}{h} = \frac{(6eV)}{\left(4.14\times10^{-15}\right)} = \boxed{1.45\times10^{15}\,Hz}$$

$$\lambda = \frac{hc}{E} = \frac{(1240)}{(6eV)} = \boxed{207nm}$$

$$f = \frac{E}{h} = \frac{(8eV)}{\left(4.14\times10^{-15}\right)} = \boxed{1.93\times10^{15}\,Hz}$$

$$\lambda = \frac{hc}{E} = \frac{(1240)}{(8eV)} = \boxed{155nm}$$

Emission: The electron drops to a lower energy level, loosing energy in the form of a photon. The electron can drop to any level, or combination of levels, below its current level. This means that one wavelength and frequency may be absorbed while others are emitted. Since some of the drops are shorter than the original absorption they do not involve as much energy. Therefore the emitted photons can have lower frequencies and longer wavelengths.

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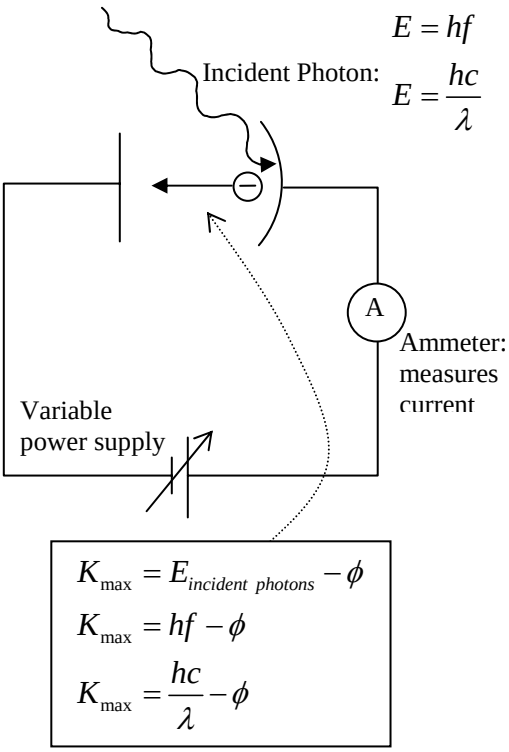
Photoelectric Effect: Young's Double Slit Diffraction experiment provided evidence that light exhibited wave properties. The photoelectric effect provided evidence of lights particle behavior. If light is shined on certain photoelectric materials a current can be induced. This requires the light to have enough energy to knock electrons out of the atoms, so a current can flow. This is the basis of solar energy. This process requires a certain minimum energy, known as the work function ϕ. So if a photon $\boxed{E = hf}$ strikes a photoelectric material some of its energy is required to move the electron completely out of the atom. This is the energy needed to ionize the atom. The kinetic energy given the electrons is the energy left over after the ionizing energy, work function, is subtracted from the photons energy. $\boxed{K_{\max} = hf - \phi}$



In photoelectric effect a photon hits a photo (light) sensitive substance. If the light hits with sufficient energy it boosts electrons past all the energy levels and the edge of the atom. If there is any extra energy left over after reaching the edge of the atom the electrons keep the excess energy. The excess energy is kinetic energy as the electrons are knocked out of the atom. If electrons have kinetic energy they are moving. If they are moving they are a current. A current flowing means electricity is flowing.

Stopping potential (V_S): The variable power supply is put in the circuit to test the strength of the electric current created by the photon collisions. The power supply is put in backwards and is adjusted until the current in the circuit is zeroed out (ammeter reads zero). If it takes 4.5V volts of electric potential (pressure) to cancel (stop) the photoelectrons from flowing then the photoelectric effect must be creating a potential of 4.5V in the opposite direction.

Kinetic Energy (K_{max}): The amount of kinetic energy the electrons have is easily determined from the stopping potential. If V_S = 4.5V, then K_{max} = 4.5eV. These are different variables with different units, but conveniently they share the same numerical magnitude (value).

Work Function (ϕ): The amount of energy needed (work that must be done) to get the electron out of the atom. Also known as ionization energy.

$K_{\max} = hf - \phi$: The energy that electrons have when they leave the atom depends on how much energy the photon had that hit it and how much of the photons energy was used to get the electron out of the atom.

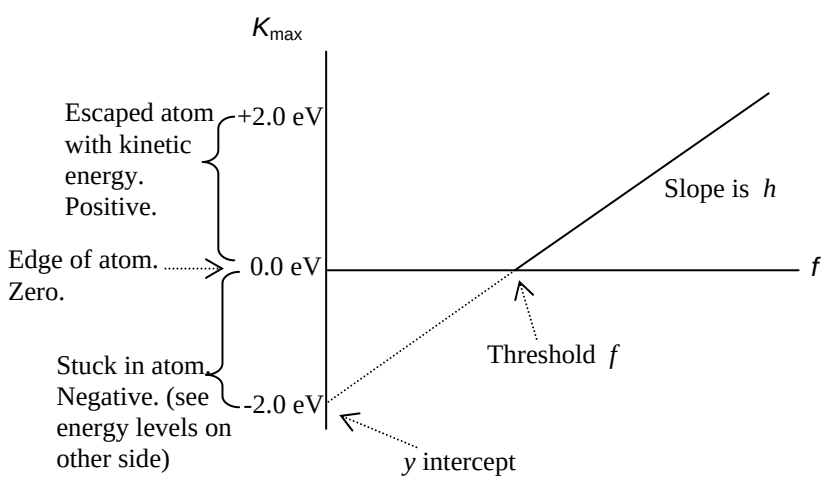
Threshold (minimum or cutoff) **frequency**: If the photon has too little energy the photoelectrons do not get out of the atom. So there is no K_{max}.

$K_{\max} = hf - \phi$ $\qquad$ $0 = hf - \phi$

Graphing Photoelectric Effect

$K_{\max} = hf - \phi$ is the equation of a line.

$y = mx + b$



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