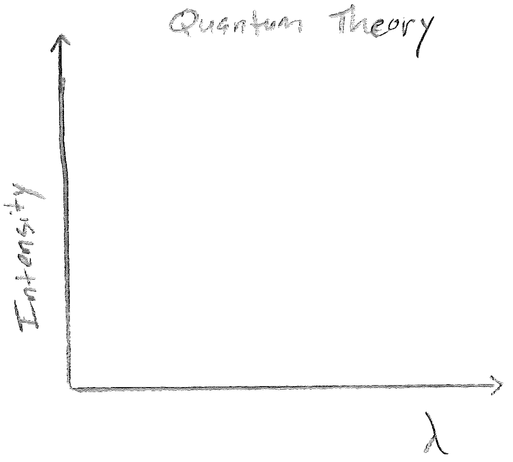
Quantum Theory

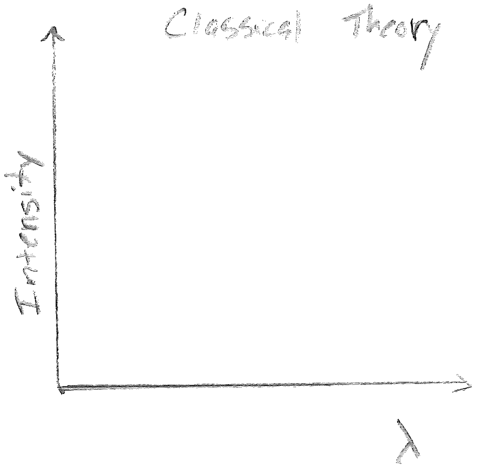
According to the E/M theory (aka the wave nature of light) energy is transferred continuously. But energy is not continuous; it exists in discrete (aka quantized) amounts. This is the beginning of Quantum Theory which began when Einstein proposed the idea of photons. Light acts as both a wave and a particle.

Key was the discovery of the electron by JJ Thompson using a cathode ray tube (measured the charge to mass ratio) and then Robert Milliken's oil drop experiment which led to the discovery of the elementary charge. Milliken discovered that the charges of oil drops are quantized which supported Quantum Theory.

A perfect black body does not reflect photons, but it can radiate photons. Black body radiation is when a blackbody is held at a constant uniform temperature it emits all wavelengths (or all frequencies) of light (continuous spectrum) within a boundary, but there are certain wavelengths that are produced in greater amounts based on the temperature of the blackbody.

1. The distribution of intensity v wavelength depends on temperature.
2. Total amount of radiation increases as temperature increases.
3. The wavelength with peak intensity decreases (increasing frequency) with increasing temperature.





Intensity is the amount of energy transmitted.

Around 1900 Plank introduced the Plank's Quantum Hypothesis which posits that the energy of any molecular oscillation is a factor of hf, so the total light energy is E = nhf while the energy of a single photon is E = hf.

Quantum Physics

The Photoelectric Effect:

when light strikes a metal, under certain conditions, electrons are emitted.

Conditions:

① If frequency is lower than the cut-off frequency, no electrons are emitted; even if you increase the intensity of the light.

② Conversely, if the frequency of the incident light is above the cut-off frequency, electrons are emitted instantly; even at low intensity.

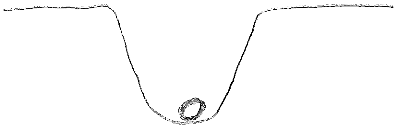
③ when electrons are emitted the kinetic energy of the emitted electrons increase as frequency increases but not as intensity increases.

Einstien suggested that the energy of electromagnetic waves was concentrated in bundles or packets called photons. Photons have no mass and **have** an energy proportional to frequency.

$$E_{photon} = hf \qquad h: \text{planck's constant} \quad h = 6.63 \times 10^{-34}\ \text{Js}$$

Photon's collide with electrons. If the photon frequency is large enough, the electron is emitted. The frequency (or energy) must be large enough to overcome the <u>work</u> <u>function</u> to remove the electron.

Analogy



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

The work function (ϕ) is specific to the metal.

$$\phi = W_0$$

Remember: $v = f \cdot \lambda$ & $c = f \cdot \lambda$ or $f = \frac{c}{\lambda}$

$$E_{photon} = h\left(\frac{c}{\lambda}\right) = \frac{hc}{\lambda}$$

Photons of light do <u>not</u> have mass, but they do have momentum.

$$P_{photon} = h/c$$

A 405 nm violet lazer light has an output power of 5mW

a.) How many photons are produced by this lazer every second?

b.) How many photons can be found in a 5m long beam?

Find the momentum of a 2cm wavelength microwave photon.

A 200 mW, 405nm lazer beam hits a mirror at normal incidence. $I = \frac{\text{Power}}{\text{Area}}$
Assuming 100% reflection, (a) find the average force on the mirror by the beam.
b.) Find the intensity of the beam at the mirror if the beam covers $10^{-5}\,m^2$?

Monochromatic light with a wavelength of 450 nm is incident on a sodium surface, $\phi = W_0 = 2.36\,eV$. What is the kinetic energy and velocity of the photoelectrons released from the sodium?

Monochromatic light with a wavelength of 546 nm releases electrons from a metal plate so that they have .33 eV of kinetic energy. With help from the table below decide what metal the plate is made of.

Metal	Na	Pt	Cs	Au
Work Function (eV)	2.28	5.66	1.94	4.83

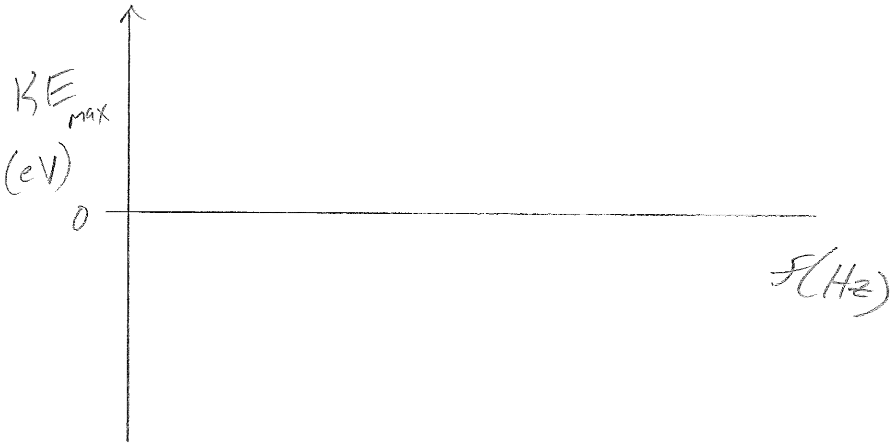
What is the minimum frequency and wavelength of light needed to emit an electron from a metal that has a work function of 4.83 eV?

Cutoff Frequency

The cut-off frequency (f_0) is the minimum frequency of incoming light below which a photocurrent will not occur.

The value of the cut-off frequency is a physical property of the metal. Each metal has its own cutoff frequency.

The value of the cut-off frequency is equal to the work function (ϕ or W_0) of the metal divided by Plancks constant.



x-intercept is equal to the cutoff frequency.

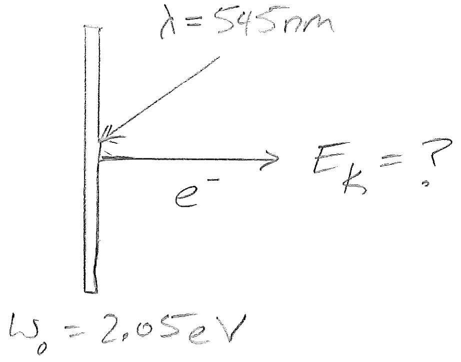
y-intercept is equal to the work function.

Slope of the line is equal to Planck's constant.

Stopping Potential is defined as the potential necessary to stop the electrons with the maximum kinetic energy from reaching the collecting plate.

A certain photo electric surface has work function 2.3 eV. If the stopping voltage is 4V and $M_e = 9.11 \times 10^{-31}$ kg Find a.) KE_{max}, V_{max} b.) λ for incident light c.) $f_{cut\ off}$

In a photoelectric effect experiment no current exists unless $\lambda \leq 600$ nm. a) $\phi = ?$ b.) $V_0 = ?$ if $\lambda = 600$nm c.) $V_0 = ?$ if $\lambda = 500$nm



1. What will be the maximum kinetic energy of the ejected electrons?
2. What will be their maximum velocity?
3. What is the stopping potential for the electrons?

Important Discoveries to Know About:

1. Rutherford's Gold Foil Experiment demonstrated the existence of a small solid center of an atom. He shot a beam of alpha particles at a sheet of gold foil; a very few number of particle were deflected back 180°.

2. Heisenberg's Uncertainty priciple considers an electron's position and momentum.
   The more accurately you measure the momentum, the less accurately you can know its position, vice versa.

3. Louis De Broglie posited that matter behaves as both particles and as waves depending on scale.

$$\lambda_{Matter} = \frac{h}{P} = \frac{h}{M \cdot V}$$

We don't see matter waves because they are so short.

a. What is $\lambda_{baseball}$ if $m_{ball} = .145\,kg$ and $V_{ball} = 20\,M/s$?

b. What is the energy using $E = P^2/2m$ or $E = \frac{1}{2}mv^2$?

$$E = \frac{p^2}{2m} = \frac{(mv)^2}{2m} = \frac{m^{\cancel{2}}v^2}{2\cancel{m}} = \frac{1}{2}mv^2$$

4. Schrodinger's Wave Equation provides the probabilities of where an electron is located within an atom.

5. Einstein, in his theory of special relativity, determined that the laws of physics are all the same for non-accelerating observers, and he showed that the speed of light is the same no matter the speed at which an observer travels.

Einstein's Special Relativity (assumes gravity is absent)

The Michael Morely Experiment demonstrated that the speed of light is constant.

The speed of light or 'c' is the cosmic speed limit.

Special relativity only applies in non-accelerating reference frames (aka objects at rest or moving in a straight line at a constant speed).

Two Postulates of Special Relativity:

1st Postulate: Laws of physics are the same in any inertial reference frame.

2nd postulate: Light emanating from a traveling source still travels at the speed of light from all perspectives or reference frames.

Time dilates and length contracts to compensate for the speed of light being the same in all reference frames.

Time slows and length contracts the closer you travel to the speed of light. Both distance and time change by the same factor to keep the speed of light constant. Example: Speed = (.5*distance)/(.5*time).

moving reference frame = moving object

stationary reference frame = observer

Light moves at the same speed in ALL non-accelerating reference frames. So if light travels a farther distance in one reference frame compare to another it is not the speed of the light that changes, it is the rate of TIME passing and the LENGTH traveled that changes.

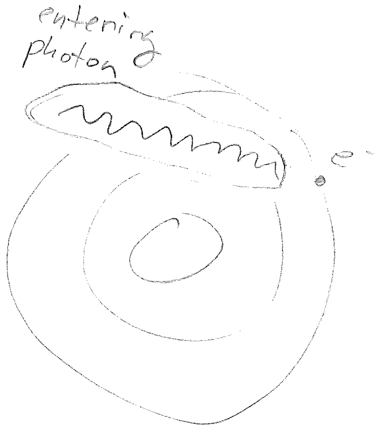
An observer of a moving object that is approaching the speed of light will see the clock on the moving object tick slower as the object approaches the speed of light. This phenomena is called 'time dilation'.

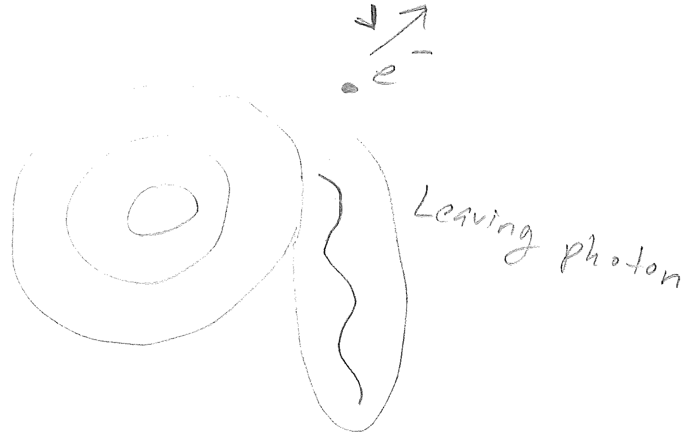
As an object approaches the speed of light its length appears to contract to an outside stationary observer, but only in the direction of its motion. This is called 'length contraction'.

Special Relativity Equations:

6. Compton Scattering is the scattering of a photon by a charged particle, usually an electron. Example:

A loosely bound outer electctron is struck by a photon. The electron only absorbs part of the photon's energy and the electron is ejected. The photon is scattered and leaves with less energy.





A photon and electron have an elastic collision and therefore momentum and energy are conserved.

$$E = hf \qquad P = \frac{h}{\lambda} = \frac{E}{c}$$

$$\lambda' - \lambda = \frac{h}{m \cdot c}(1 - \cos\theta)$$

$\frac{h}{mc} = \lambda_c$ compton wavelength $= 2.4$ picometers

Large effect if $\lambda << \lambda_c$

Small effect if $\lambda >> \lambda_c$

⑦ Pair Annihilation: If an e^- and a e^+ collide, they annihilate each other and create γ-ray photons.

mass-energy conservation:

before

$$KE_{e^- \& e^+} + 2m_{e^-}c^2 = \text{Energy of Photons}$$

Pair production: A γ-ray photon can become an electron and a positron. The γ-ray photon must be high energy and near a nucleus.

1.) What is the energy of a γ-ray photon if it produces an electron-positron pair with a total KE of 2 MeV?
$(m_{e^-} = 9.11 \times 10^{-31}\,kg = 0.511\ MeV/c^2)$

2.) An e^- & e^+ traveling at the same speed of 5000 m/s in opposite directions collide with each other and produce 2 identical γ-ray photons. Find the photon energy of each photon.

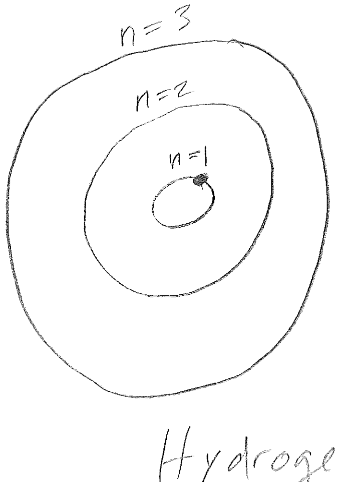
⑧ Principle of Complementarity by Neils Bohr

To understand any given experiment we must use either the wave or photon theory, but not both.
Bohr took Rutherford's Planetary atom model and added quantum ideas.

The Bohr Model & Energy State Transitions of e^- in atoms

Why are electrons not pulled into the nucleus?

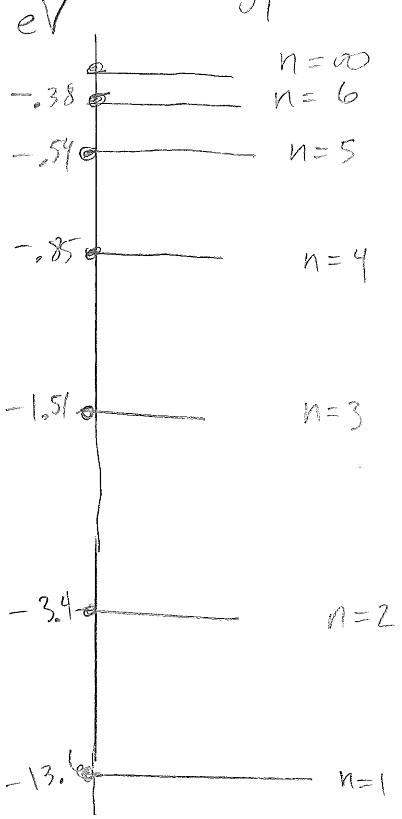
Rutherford suggested that electrons orbit the nucleus, but this did not correspond with electromagnetism because moving electrons emit waves of continuous energy. Bohr said that electrons orbit the nucleus but only certain orbits are allowed and that energy only changes when electrons change orbits.



Each spectrum line corresponds to, whether emitting or absorbing, an electron transition between energy levels.

Higher to n=1 energy level is the Lyman series.
Higher to n=3 energy level is the Paschen series
Transitions down to n = 2 is the Balmer Series.
The Balmer Series produces visible light.
The Lyman series produces UV light.

Hydrogen
Energy Level Diagram



$hf = E_{upper} - E_{lower}$

$hf_1 = E_5 - E_2$ Series?

$hf_2 = E_6 - E_3$ Series?

$hf_3 = E_2 - E_1$ Series?

Balmer $\Delta E = 2.86\,eV$ for $n=5$ to $n=2$.

1 Convert 2.86eV to Joules:

2 Find the frequency of the 2.86eV photon. $E = hf$

3 Find the wavelength of the photon. $c = f \cdot \lambda$

Lyman $\Delta E = 10.2\,eV$ for $n=2$ to $n=1$

4 Convert 10eV to Joules:

5 Find the frequency of the 10.2eV photon.

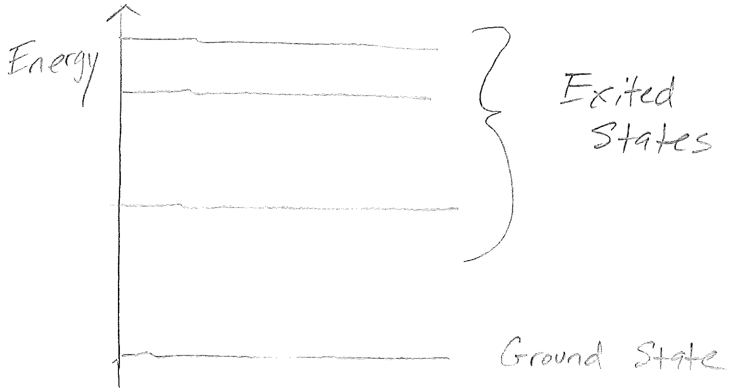
6 Find the wavelength of the photon.

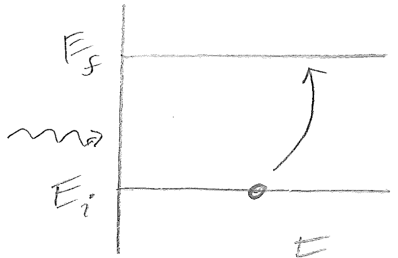
Line Spectra & Energy Levels

Pure white light has a continuous spectrum.

Gases, with molecules far apart, produce a line spectrum.

Bohr explained this phenomenon with discrete energy levels.

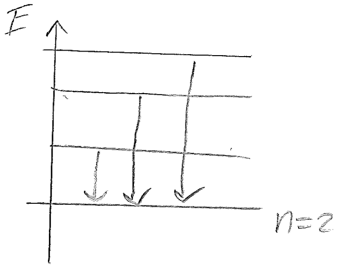




$$E_{photon} = |E_f - E_i|$$

For spontaneous absorption to occur the photon striking the electron must have exactly the right amount of energy.

Balmer's Formula



The hydrogen atom has a line spectrum some of which fall within the visible spectrum.
As the electrons transition from higher to lower energy levels photons are emitted.

$$1/\lambda = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad n \geq 3$$

R_H: Rydberg's Constant
$R_H = 1.097\times10^{7}\,m^{-1}$

$$E_{photon} = \frac{hc}{\lambda} = hcR_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right) = \underbrace{\frac{hcR_H}{2^2}}_{E_f} - \underbrace{\frac{hcR_H}{n^2}}_{E_i}$$

More general form:

$$1/\lambda = R_H\left(\frac{1}{n_{final}^2} - \frac{1}{n_{initial}^2}\right)$$

Absorption

What is the wavelength of light that hydrogen in its ground state would absorb for its electron to reach $n=3$?

What wavelength photon would be required to ionize a hydrogen atom in the $n=2$ state?

The Bohr radius is a physical constant, approximately equal to the most probable distance between the nucleus and the electron in a hydrogen atom in its ground state.

Bohr Energy Levels: Total Energy = KE + PE

Electron Velocity

a. what is the longest λ EM radiation capable of ionizing hydrogen atoms at $n=3$? b. what energy photon is needed to ionize the hydrogen atom at $n=3$ and to give ejected e^- 5eV of Kinetic energy?

A photon is emitted as a hydrogen atom undergoes $n=5$ to $n=2$. Find a) the energy & λ of the photon b.) what energy photon, when absor~~bed~~ by this hydrogen atom can cause the e^- to transition from $n=2$ back to $n=5$? c.) Can a photon with 2.88 eV cause the e^- to go from $n=2$ back to $n=5$?

A hydrogen atom initially in its ground state absorbs a photon and transitions to $n=3$. a.) What is the energy of the absorbed photon? b.) If the atom eventually transitions back to ground state, what possible energy photon(s) can the atom emit in the process?

Consider the following 4 transitions for a hydrogen atom:

a.) $n=2$ to $n=4$

b.) $n=2$ to $n=1$

c.) $n=6$ to $n=2$

d.) $n=3$ to $n=5$

1. Which of the transitions will emit the shortest λ photon?

2. Which of them will cause the atom to gain the most energy?