King Saud University
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Quantum Theory of Light

General Physics II
PHYS 111

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Outline

- Definition
- The Birth of the Quantum
- Planck's constant
- Photons
- Definition of a black body
- Blackbody Radiation
- Implications of Planck's Law
- Photoelectric Effect

Outline

- Photoelectric Fact #1,2,3
- Wave-Particle Duality
- De Broglie Wavelength
- Compton Effect
- Heisenberg’s Uncertainty Principal
- The Electromagnetic Spectrum
- Is light a wave or a particle?
- Questions

Definition

- ***Quantum theory*** is a theory needed to describe physics on a microscopic scale, such as on the scale of atoms, molecules ,electrons, protons, etc.
- **It** tells us that both light and matter consists of tiny particles which have **wavelike properties** associated with them.
  - **Light** is composed of particles called photons
  - **matter** is composed of particles called electrons, protons, neutrons.
  - It's only when the mass of a particle gets small enough that its wavelike properties show up.

The Birth of the Quantum

- Max Planck made two assumptions
  - Firstly the energy contained in radiation is related to the frequency of the radiation by the relationship

$$E = nhf$$

    - *n* is a positive integer called the *quantum number*
    - *f* is the frequency of the oscillation
  - Second, the molecules in the walls can only absorb energy in discreet packets, later to become known as “photons

Planck's constant

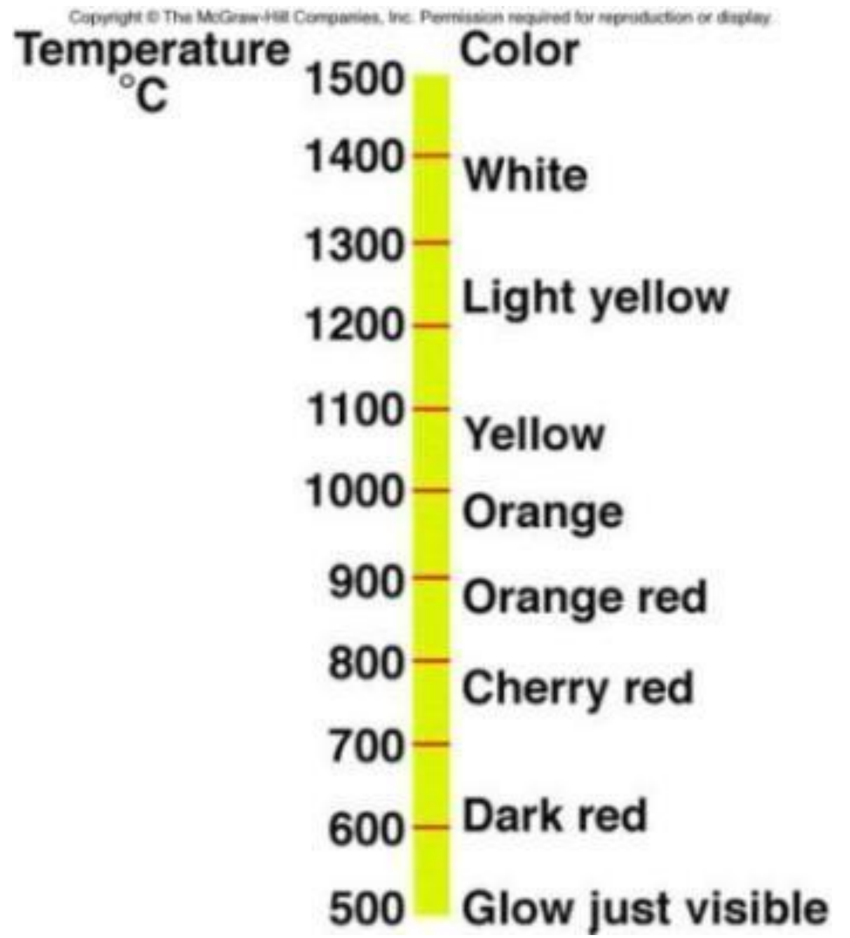
- Planck proposed that light could only have certain energies

$$E=hf$$

- Then the energy of oscillators in the black body could only have certain fixed values

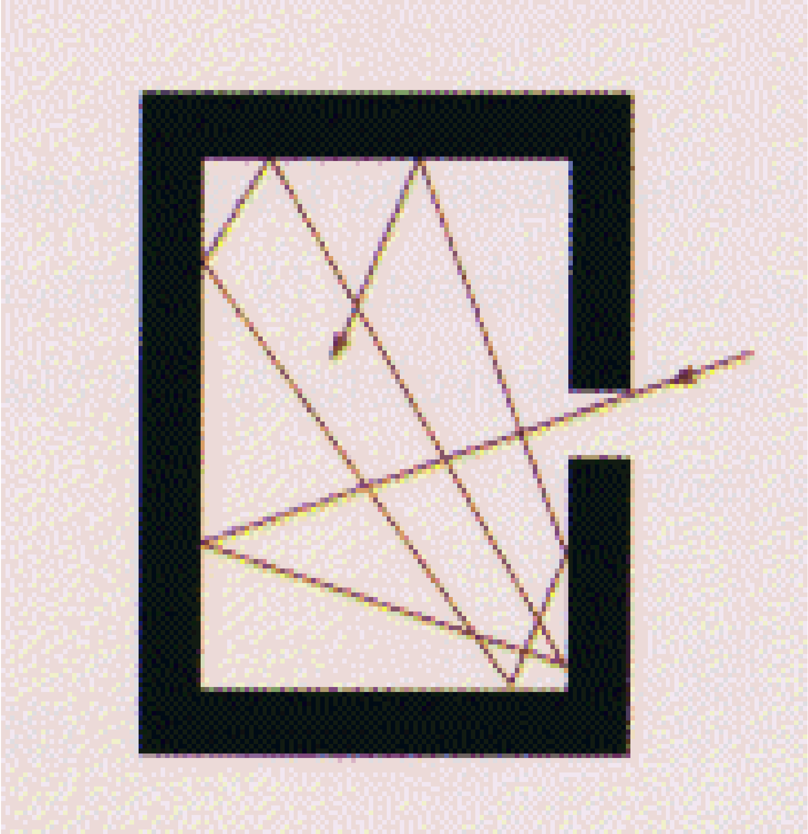
Photons

- **Max Planck** in 1900 stated that the light emitted by a hot object (black body radiation) is given off in discrete units or quanta. The higher the frequency of the light, the greater the energy per quantum



Definition of a black body

- A black body is an ideal body which allows the whole of the incident radiation to pass into itself (without reflecting the energy) and absorbs within itself this whole incident radiation (without passing on the energy).
- This property is valid for radiation corresponding to all wavelengths and to all angels of incidence. Therefore, the black body is an ideal absorber of incident radiation.

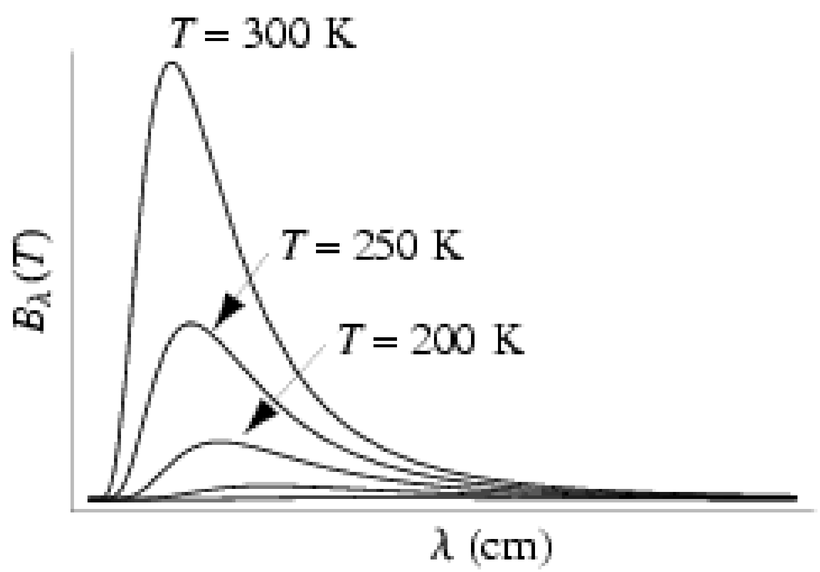


Blackbody Radiation

- An object at any temperature emits radiation
  - The wavelength of the radiation decreases as the body gets hotter
- A black-body is a perfect absorber
  - It does not reflect ambient light
  - The only light coming from the body is the radiation of the body itself
- The light from a black-body is in thermal equilibrium with the body
- This radiation has two important properties,
  - The peak wavelength decreases with increasing temperature
  - The total power emitted increases with increasing temperature

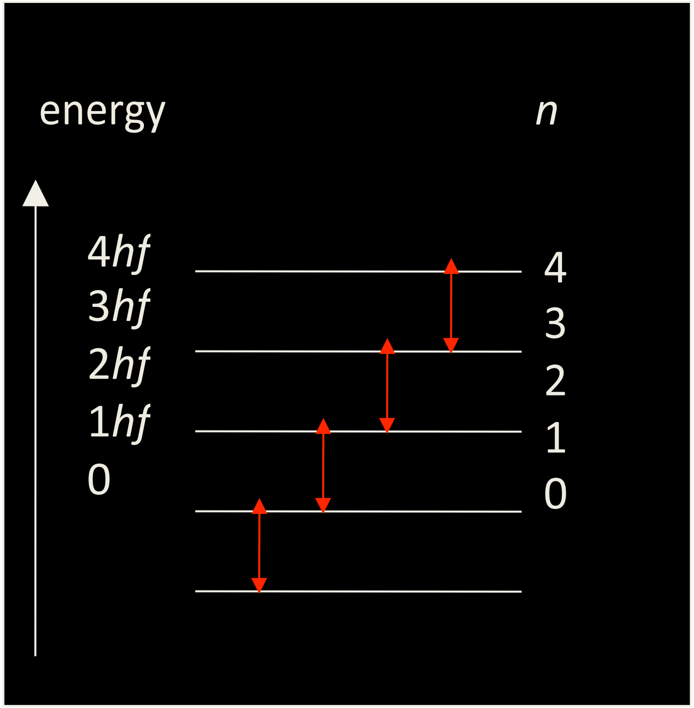
Black-Body Radiation

- ***The Planck Law*** gives a distribution that peaks at a certain wavelength, the peak shifts to shorter wavelengths for higher temperatures, and the ar under the curve grows rapidly with increasing temperature



Implications of Planck's Law

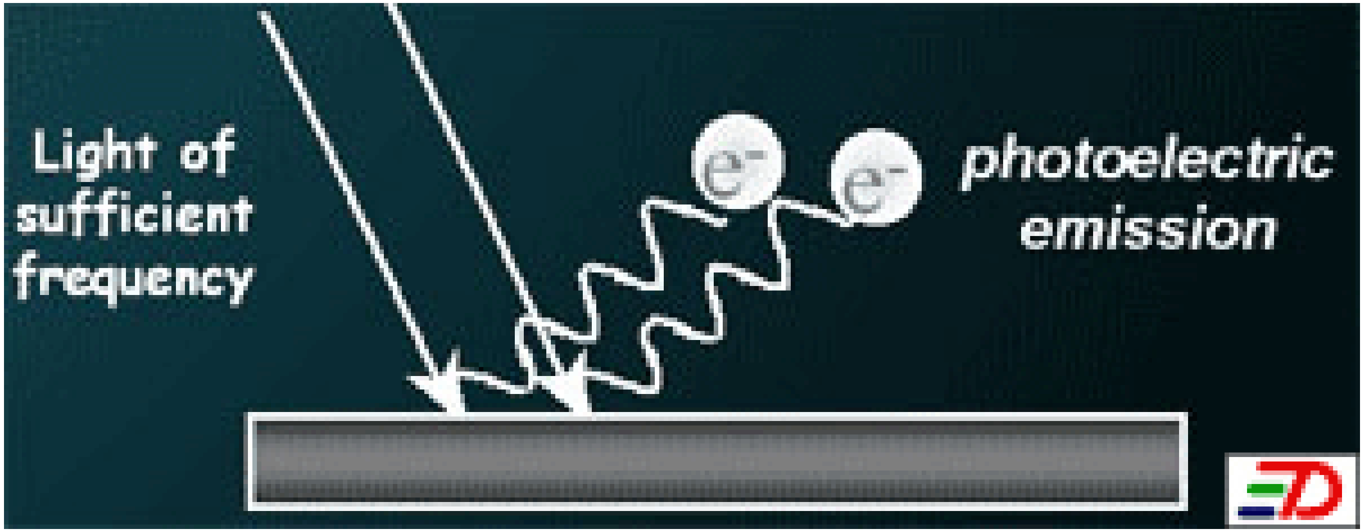
- The energy levels of the molecules must be discreet.
- Only transitions by an amount E=*hf* are allowed.
- The implication is that light exists in discrete quanta of energy.



These quantum levels are now known as number states

Photoelectric Effect

- One of the most popular concepts concerning Quantum Mechanics is called , "The Photoelectric Effect". In 1905, Albert Einstein published this theory for which he won the Nobel Prize in 1921.
- *When light strikes a material, electrons are emitted. The radiant energy supplies the work necessary to free the electrons from the surface."*



Photoelectric Fact #1

- The LIGHT ENERGY (E) is in the form of quanta called PHOTONS. Since light is an electromagnetic wave it has an oscillating electric field. The more intense the light the more the field oscillates. In other words, its frequency is greater.

$$E = Energy \ \alpha \ f$$

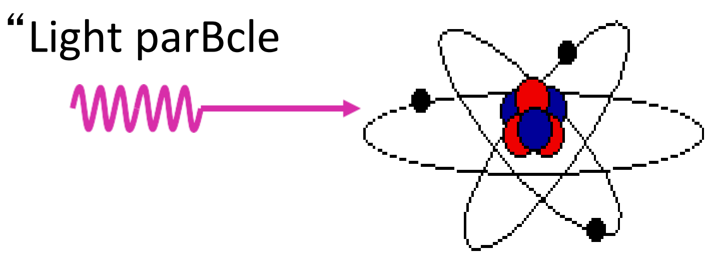
$$h = \text{Constant of Proportionality}$$

$$h = \text{Planck's Constant} = 6.63x10^{-34} \ Js$$

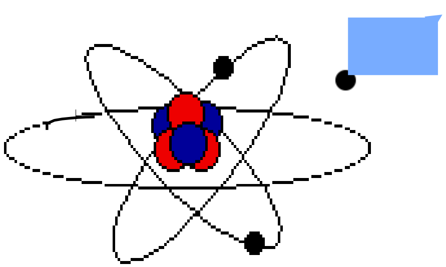
$$E = hf$$

Photoelectric Fact #1

- the energy of the light particle (photon) must overcome the *binding energy* of the electron to the nucleus.
- If the energy of the photon exceeds the binding energy, the electron is emitted with a $KE = E_{photon} - E_{binding}$.
- The energy of the photon is given by **E=hf,** where the constant $h = 6.6 \times 10^{-34}$ [J s] is Planck's constant.



Before Collision

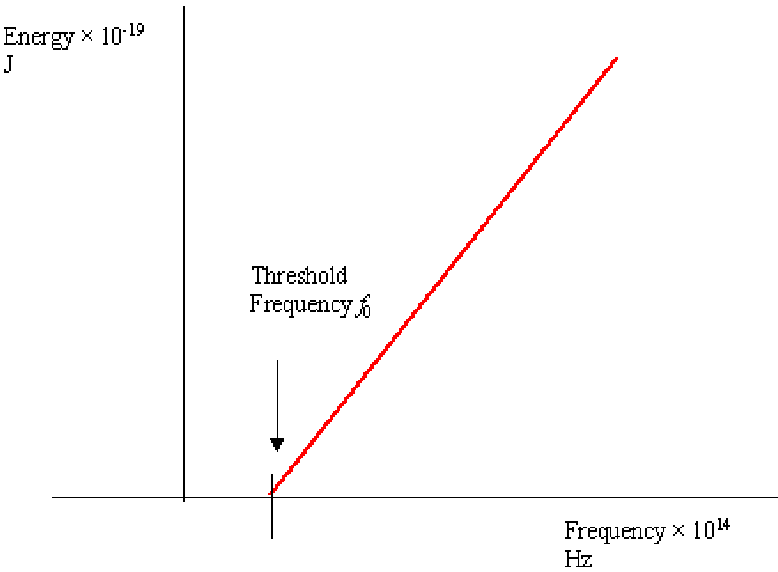


A-er Collision

Photoelectric Fact #1

- Planck's Constant is the SLOPE of an Energy vs. Frequency graph!
- **Make sure you USE the correct constant!**

h	***hc***
6.63×10^{-34} Js	1.99×10^{-25} Jm
4.14×10^{-15} eVs	1.24×10^{3} eVnm



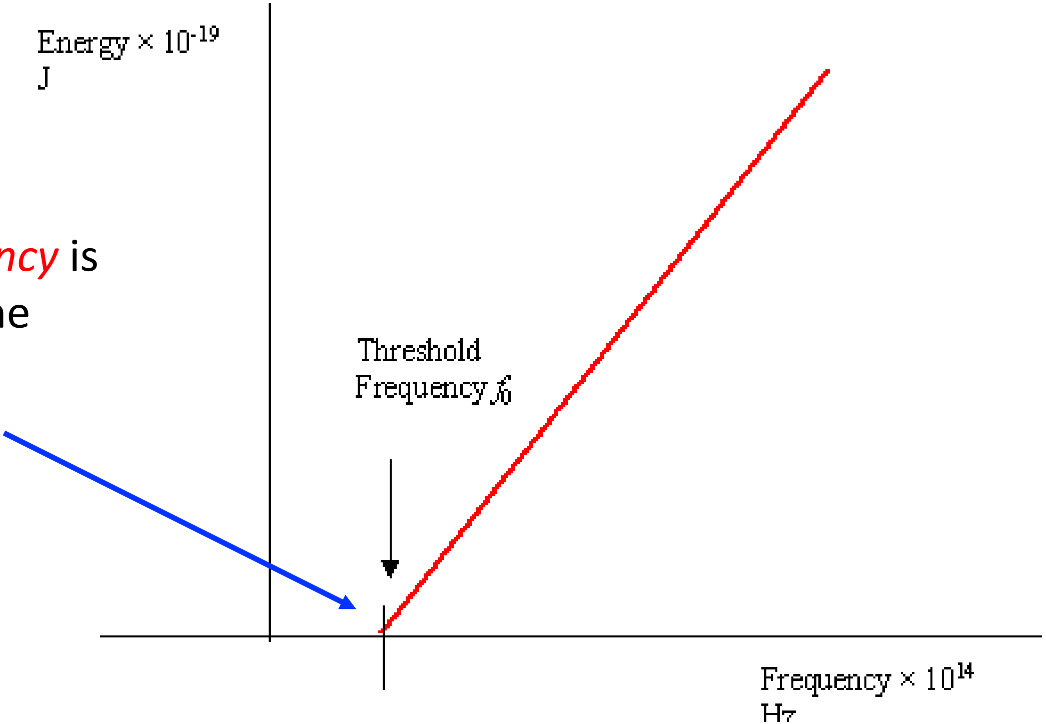
$$E \alpha f \rightarrow E = hf \rightarrow \frac{E}{f} = h$$

$$\frac{c}{\lambda} = f \rightarrow E = \frac{hc}{\lambda}$$

Photoelectric Fact #2

- **The frequency of radiation must be above a certain value before the energy is enough. This minimum frequency required by the source of electromagnetic radiation to just liberate electrons from the metal is known as *threshold frequency, f_0***

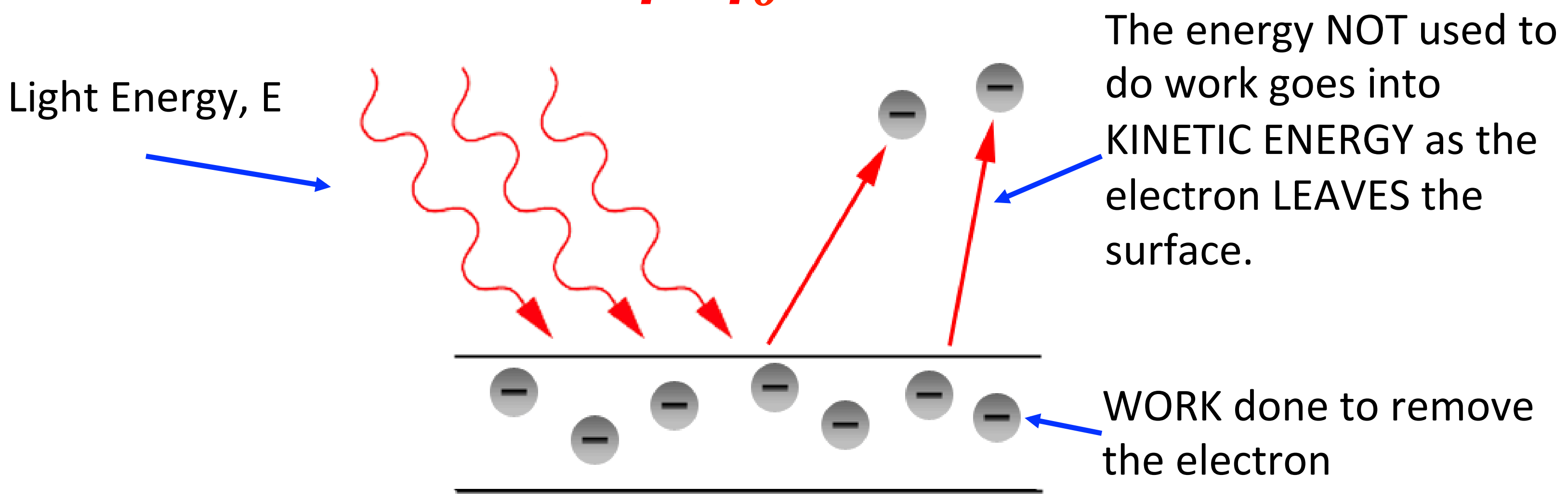
The *threshold frequency* is the X---intercept of the Energy vs. Frequency graph!



Photoelectric Fact #3

The MAXIMUM KINETIC ENERGY is the energy difference between the MINIMUM AMOUNT of energy needed (ie. the work function) and the LIGHT ENERGY of the incident photon.

$$KE=hf-hf_o$$



Photoelectric Fact #3

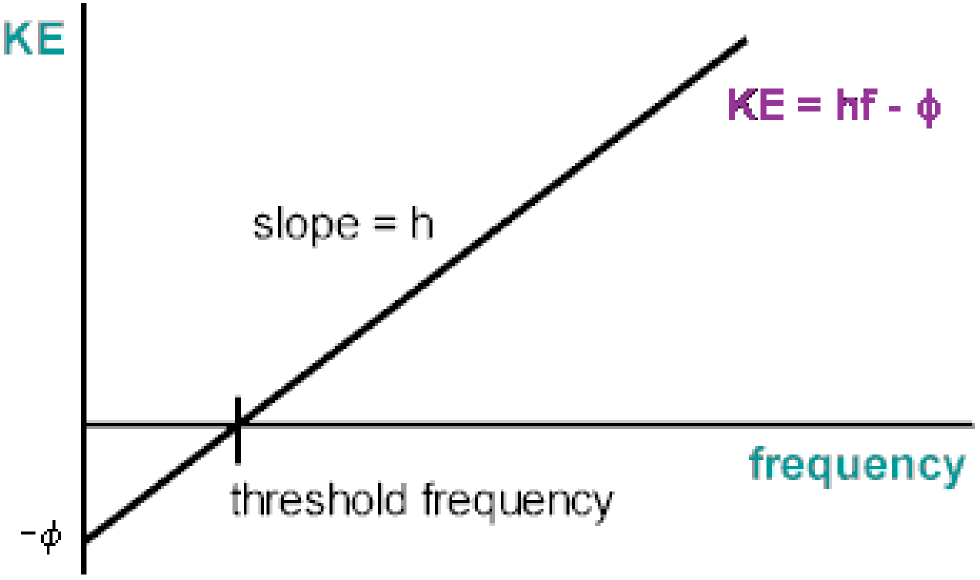
KINETIC ENERGY can be plotted on the y axis and FREQUENCY on the x-axis. The WORK FUNCTION is the y – intercept as the THRESHOLD FREQUNECY is the x intercept. PLANCK 'S CONSTANT is the slope of the graph.

$$E = hf$$

$$K + W = hf$$

$$K = hf - W \rightarrow K = hf - \phi$$

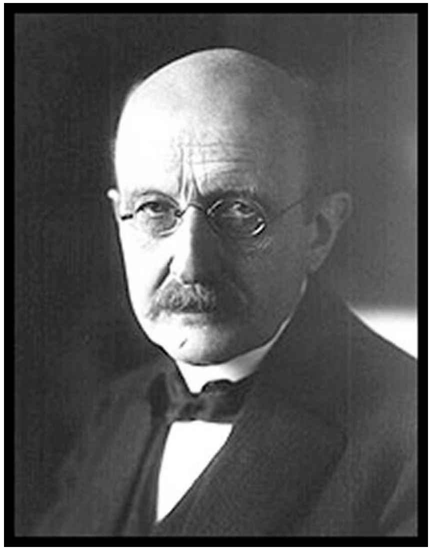
$$y = mx + b$$



Wave-Particle Duality

The results of the photoelectric effect allowed us to look at light completely different.

First we have Thomas Young's Diffraction experiment proving that light behaved as a WAVE due to constructive and destructive interference.



- Then we have Max Planck who allowed Einstein to build his photoelectric effect idea around the concept that light is composed of PARTICLES called quanta.

De Broglie Wavelength

- If light is a WAVE and is ALSO a particle, does that mean ALL MATTER behave as waves?

That was the question that Louis de Broglie pondered. He used Einstein's famous equation to answer this question.

$$E = mc^2$$

$$E = mcc,\ p = mc$$

$$E = pc$$

$$E = hf$$

$$hf = pc,\ c = \lambda f$$

$$p = \frac{h}{\lambda}$$

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \text{De Broglie Wavelength}$$

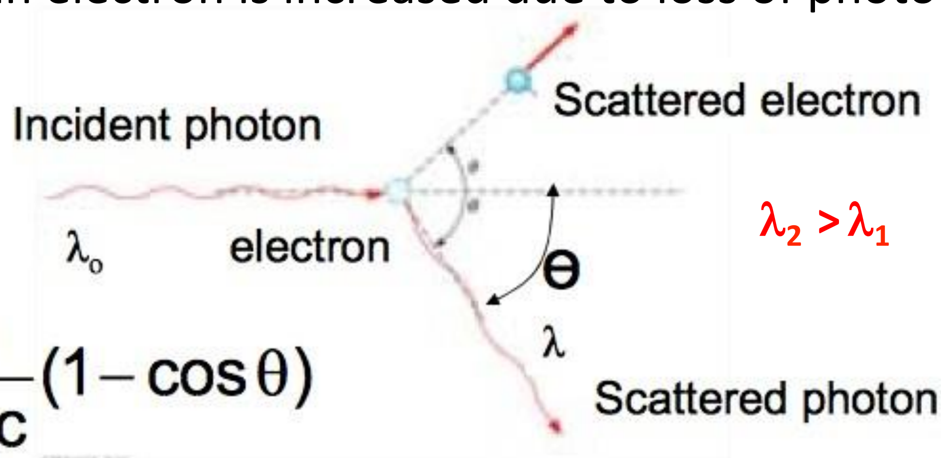
De Broglie Wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \text{De Broglie Wavelength}$$

- **YOU are a mater WAVE!**
- Basically all mater could be said to have a momentum as it moves. The momentum however is inversely proportional to the wavelength. So since your momentum would be large normally, your wavelength would be too small to measure for any practical purposes.
- An electron, however, due to it's mass, would have a very small momentum relative to a person and thus a large enough wavelength to measure thus producing measurable results.
- This led us to start using the Electron Microscopes rather than traditional Light microscopes.

Compton Effect

- The Compton effect is based on treating light as consisting of particles of a given energy related to the frequency of the light wave.
- In 1924, A. H. Compton performed an experiment where X---rays impinged on mater, and he measured the scattered radiation.
- High energy photons knock electrons out of atoms. The wavelength of a photon scattered from an electron is increased due to loss of photon energy.



$\lambda_2 > \lambda_1$

$$\Delta\lambda = \lambda - \lambda_o = \frac{h}{m_e c}(1 - \cos\theta)$$

where me is the mass of the electron and me c2 = 511 keV = .511 MeV.

Lower energy –> Longer wavelength

Compton Effect

- Compton found that if you treat the photons as if they were particles
  of zero mass, with energy **$E=hc/\lambda$** and momentum $p=h/\lambda$

  ➔➔ The collision behaves just as if it were 2 billiard balls colliding !

  Photon behaves like a particle with energy & momentum as given above!

Heisenberg's Uncertainty Principal

- Quantum theory tells us that

If you know where something is, you cannot also know its momentum

If you know the energy of the object, you cannot also know the time at which the object had that energy

many scientists had a hard time buying this idea…"NON DETERMINISTIC"

Uncertainty

Change (uncertainty) in posiBon

Change (uncertainty) in MOMENTUM

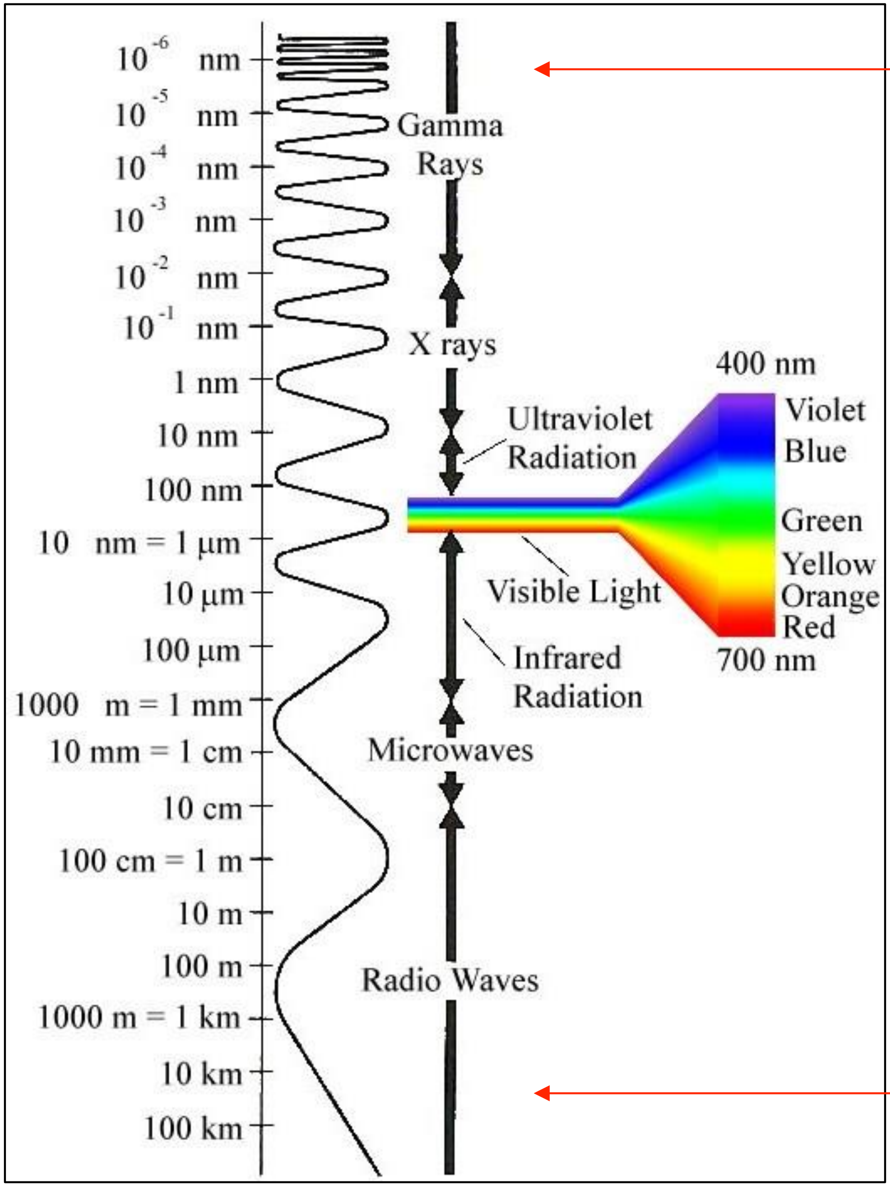
$$\otimes \chi \times \otimes p > h / 4\pi$$

Uncertainty

- For LARGE objects, uncertainty is SMALL
- For small objects (like atoms and electrons) the uncertainty is LARGE
- Plank's constant is VERY VERY SMALL

$$6.626068 \times 10^{-34}\ m^2kg/s$$

The Electromagnetic Spectrum



Shortest wavelengths
(Most energetic photons)

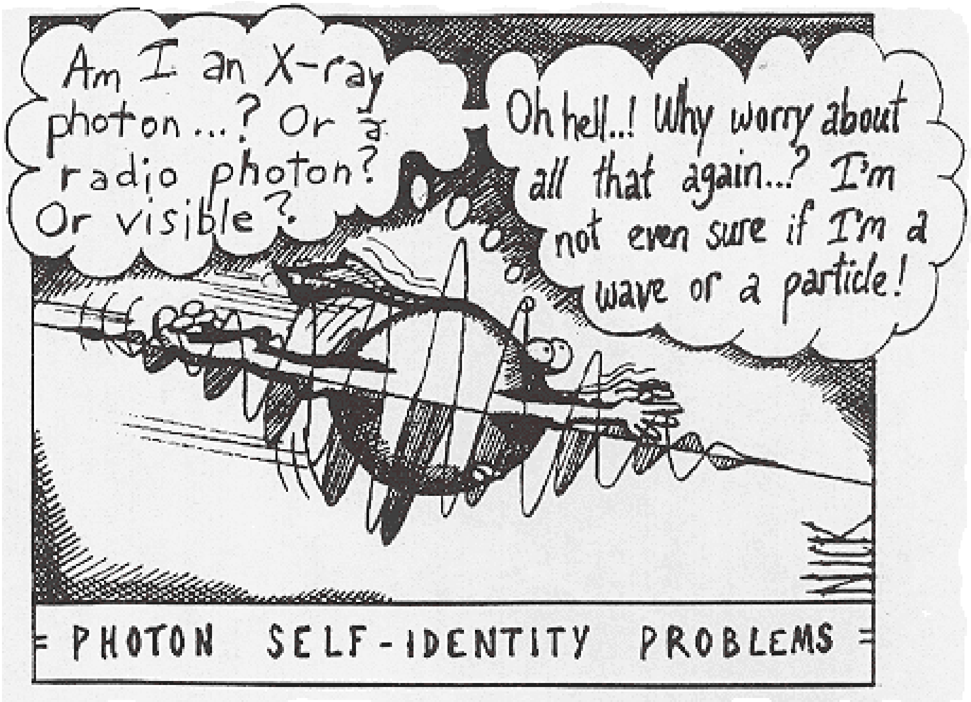
$$E = h\nu = hc/\lambda$$

h=6.6x10^{---34}
[J*sec] (Planck's

Longest wavelengths
(Least energeBc photons)

Is light a wave or a particle ?

- So is light a wave or a particle ?
- On macroscopic scales, we can treat a large number of photons as a wave.
- When dealing with subatomic phenomenon, we are often dealing with a single photon, or a few.



In this case, you cannot use the wave description of light. It doesn't work.

Questions

- In the Compton experiment, the wavelength of the scattered light is ________ the wavelength of the incident light.

(A) longer than

(B) the same as

(C) shorter than

Questions

- Suppose visible light of wavelength = 5 x 10^{-7} m is used to determine the position of an electron to within the wavelength of the light. What is the minimum uncertainty in the electron's speed?

Questions

- (a)Calculate the wavelength in meters of an electron traveling at 1.24×10^{7} m/s. The mass of an electron is 9.11×10^{-28} g.

Questions

- A green line of wavelength 4.86×10^{7} m is observed in the emission spectrum of hydrogen. Calculate the energy of one photon of this green light.

Questions

Planck's constant………….

A) remains unknown to this day.

B) is the inverse of Einstein's constant.

C) is used to find the quantum energy associated with a certain frequency of light.

D) is not really constant since it varies from one part of the universe to another.

Questions

- A light source of wavelength λ illuminates a metal and ejects photoelectrons with a maximum kinetic energy of 1.00 eV. A second light source with half the wavelength of the first ejects photoelectrons with a maximum kinetic energy of 4.00 eV. • Determine the work function of the metal.

Questions

Which statement is TRUE?

A) Light always behaves like a wave and electrons always behave like particles.

B) Light always behaves like a particle and electrons always behave like waves.

C) Both light and electrons behave sometimes like waves and sometimes like particles.

D) Light and electrons never behave like waves or particles.

Questions

How many Joules of energy are contained in a photon with λ = 550 nm?

Questions

What is the energy of a quantum of light with a frequency of 3.87×10^{19} Hz?