5.111 Lecture Summary #3 **Monday, September 8, 2014**

Reading for today: Section 1.2 and Section 1.4 with a focus on pgs 10-12 (*4th ed* or *5th ed*).
Read for Lecture 4: Section 1.5 – The Wave-Particle Duality of Matter, and Section 1.6 – The Uncertainty Principle. (Same sections in *4th ed*. or *5th ed.*)

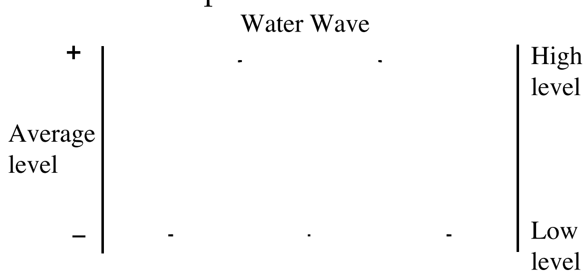
Topics: **The wave-particle duality of light**
I. Light as a wave, characteristics of waves
II. Light as a particle, the photoelectric effect

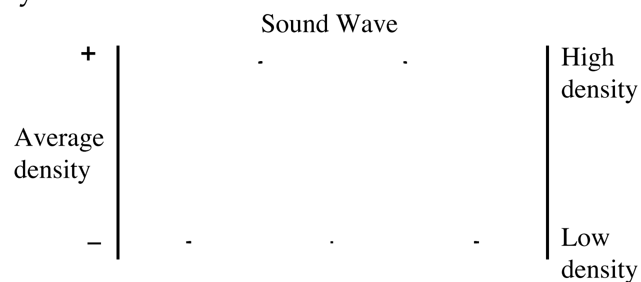
With the discovery of subatomic particles, the need for a new type of mechanics (Quantum mechanics) began to emerge. To explain the observations that scientists were making, two tenets were required: **1. Radiation and matter display both wavelike and particle-like properties**; and **2. Energy is quantized into discrete packets (called photons).**

THE WAVE-PARTICLE DUALITY OF LIGHT

LIGHT AS A WAVE; CHARACTERISTICS OF WAVES

Waves have a periodic variation of some quantity.





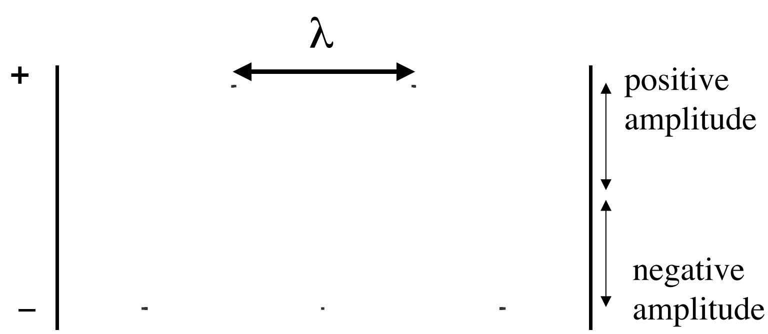
Light (______________________ radiation) is the periodic variation of an electric field.

We can characterize electromagnetic radiation (or any wave) in terms of:

Amplitude (a): the deviation from an average level. Can have (+) or (-) value.

Wavelength (λ): the __________________ between successive maxima or minima

Frequency (ν): the number of _______________ per unit time



$1/\nu$ = ________________ = the time for one cycle to occur

Units of frequency (ν) : cycles per second = _______

Intensity of a wave = __________

We can calculate the speed of a wave:

Speed = distance traveled / time elapsed = _____________ = ___________

Electromagnetic radiation has a constant speed, c (the "speed of light").

$$\mathbf{c = \lambda\nu =} \text{ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ } \mathbf{ms^{-1}}$$

For any wavelength of light, the product of λ * ν is always c. **λ and ν are NOT independent** of each other. If you know λ, you can calculate ν. If you know ν, you can calculate λ.

The color of visible light waves is determined by their wavelength:

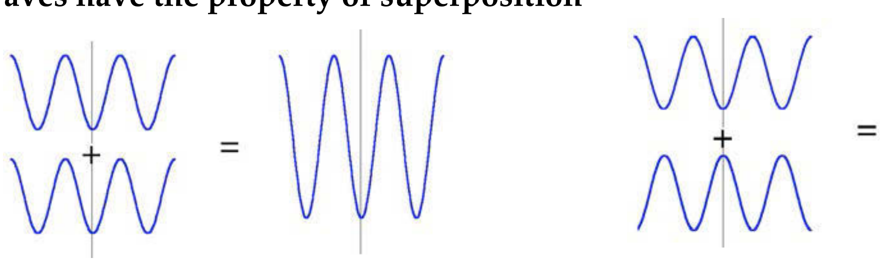
RED has longest λ	~700 nm (7.0×10^{-7} m)	and ____________ ν	~4.3×10^{14} Hz
ORANGE	~620 nm (6.2×10^{-7} m)		
YELLOW	~580 nm (5.8×10^{-7} m)		
GREEN	~530 nm (5.3×10^{-7} m)		
BLUE	~470 nm (4.7×10^{-7} m)		
VIOLET has shortest λ	~420 nm (4.2×10^{-7} m)	and highest ν	~7.1×10^{14} Hz

Visible light is only a small part of the entire electromagnetic spectrum:

radio waves	λ = 1 m to 10^5 m
microwaves	λ = 1 mm to 1 m
infrared	λ = 750 nm to 1 mm
visible	λ = 390 nm to 750 nm
ultraviolet	λ = 10 nm to 400 nm
X-rays	λ = 0.01 nm 10 nm
gamma-rays	λ < 0.02 nm

(You are not responsible for knowing specific wavelength or frequency ranges, but you should know the relative order of colors and types of waves.)

Waves have the property of superposition

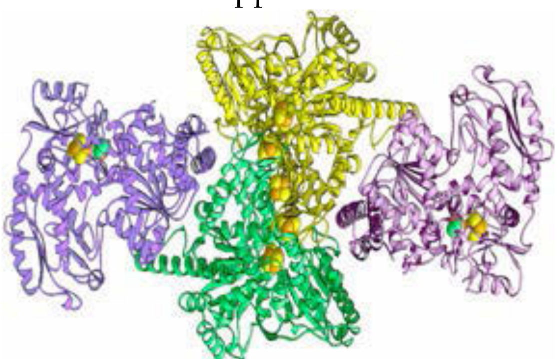


in phase constructive interference out-of-phase destructive interference

Wave interference is important for many reasons, including: the design of symphony halls; noise-cancelling technology; and determining three-dimensional structures of proteins and nucleic acids at atomic resolution…

In their own words:

Prof. Cathy Drennan and her lab members use the principles of constructive / destructive interference, and other properties of light (energy, frequency, and intensity) in their research using X-ray crystallography to determine the structure of proteins. The Drennan lab captures "snapshots" of proteins in action with a focus on proteins with medical or environmental applications.

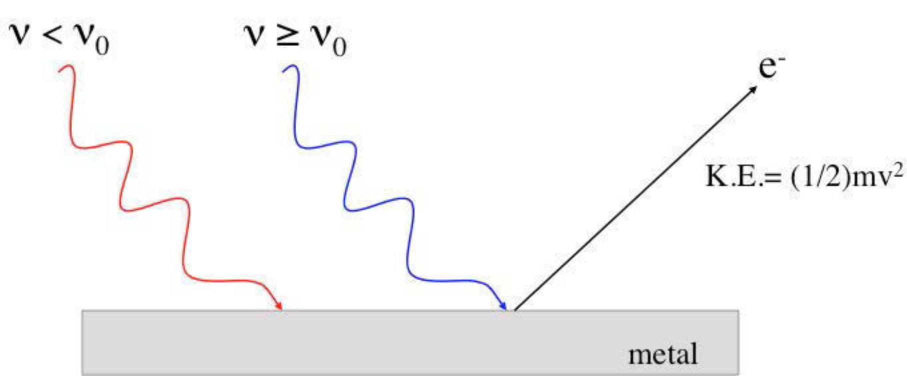


Drennan lab research webpage: http://drennan.mit.edu/.

II. LIGHT AS A PARTICLE

The Photoelectric Effect

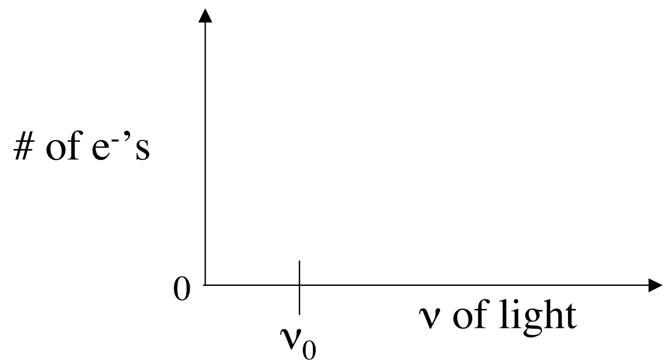
A beam of light hitting a metal surface can eject electrons.



K.E. (Kinetic Energy)
m (mass)
v (velocity)

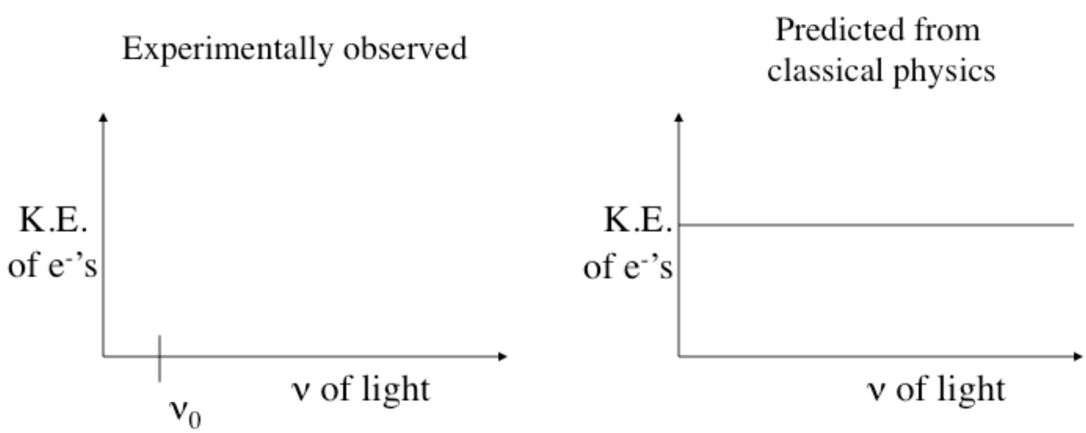
The frequency, ν, of the incoming light must be equal to some threshold frequency, _____ , for an electron to be emitted. The ν_0 value depends on the identity of the metal.

At a constant intensity, the **frequency** of the light has no effect on the **number of electrons** ejected, as long as the frequency is above ν_0. (Below ν_0, no electrons are emitted.)

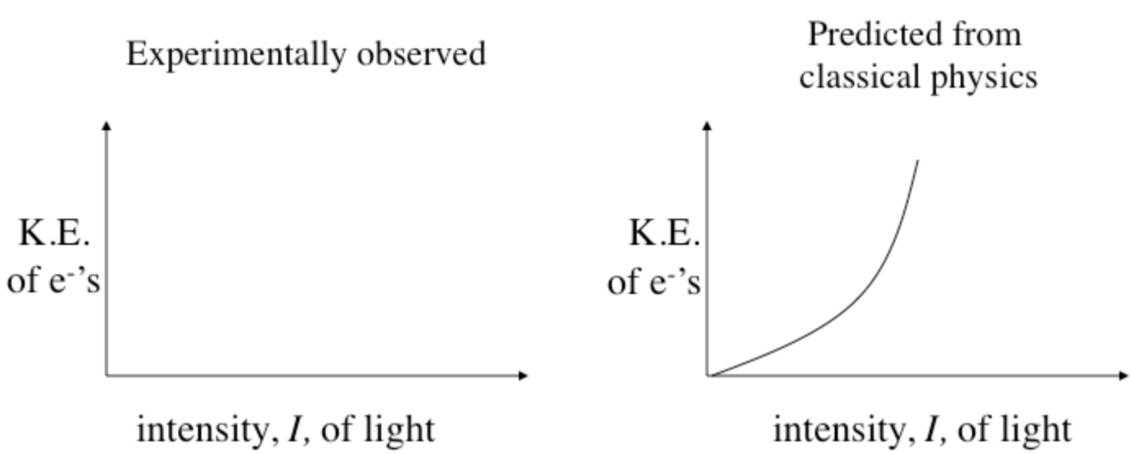


Scientist kept studying the photoelectric effect and surprising kept coming:

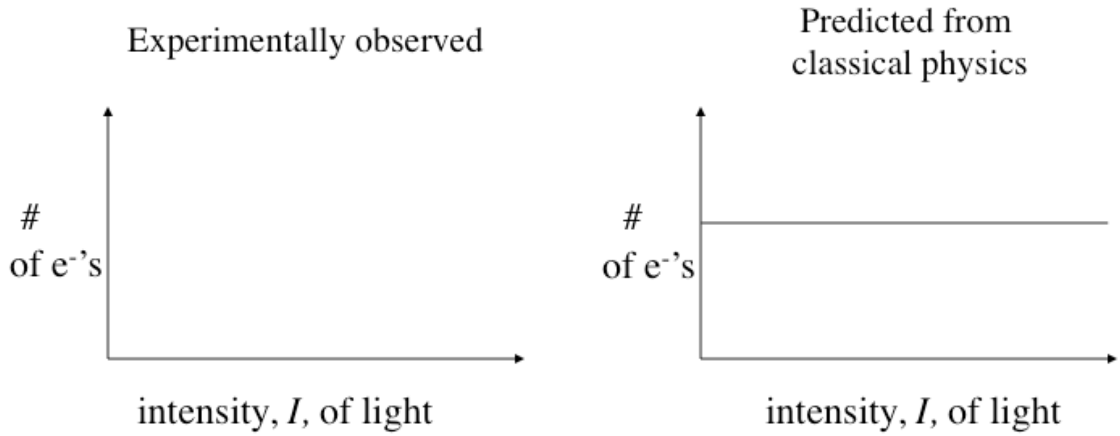
The kinetic energy, **K.E.**, of ejected electros was measured as function of the **frequency** (ν) of the incident light:



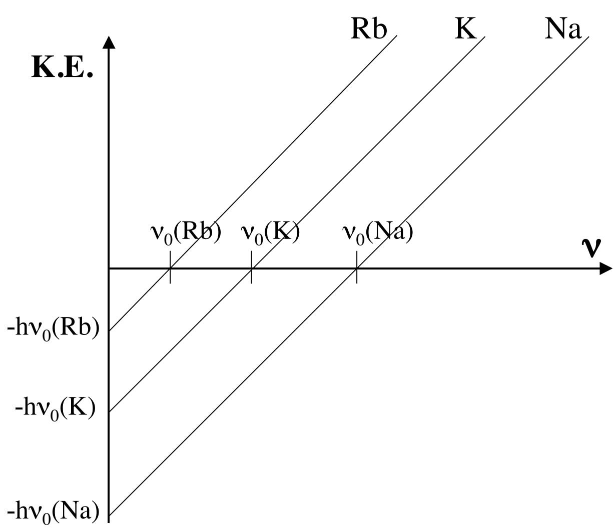
The kinetic energy, **K.E.**, of the ejected electrons was measured as a function of **intensity** of the incident light.



The # **of electrons** ejected was measured as a function of **intensity** of the incident light.



These data were in direct opposition to the predictions of classical mechanics. In 1905 Einstein analyzed plots of K.E. as a function of frequency for different metals and found that all of the data fit into a linear form



y = mx + b

slope (m) = ______________________

6.626×10^{-34} Js = **Planck's constant** = _____

y-intercept (b) = - hν_0

Einstein could rewrite the equation of the line:

$$y = mx + b$$

K.E. = ____________________

ν = frequency of incident light

hν = the **energy of the incident light** = $\mathbf{E_i}$

ν_0 = threshold frequency

hν_0 = threshold energy or **workfunction (ϕ)**

Einstein postulated (1905)

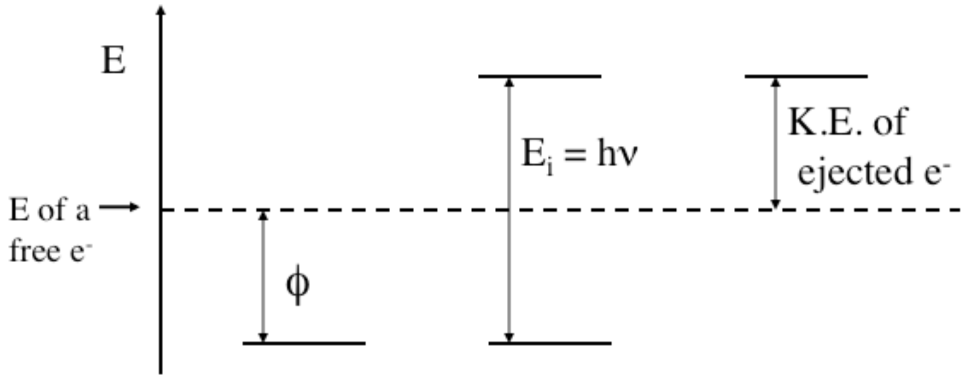
1) The energy of a photon is proportional to its frequency!!!

E = hν (Note Units: Joules (J) = (Js)(s^{-1}))

2) Light is made up of energy "packets" called "photons"

This provided a new model for the photoelectric effect

The energy of an incoming photon (E_i) must be equal to or greater than the workfunction (ϕ) of the metal in order to eject an electron. Any "leftover" energy is K.E.



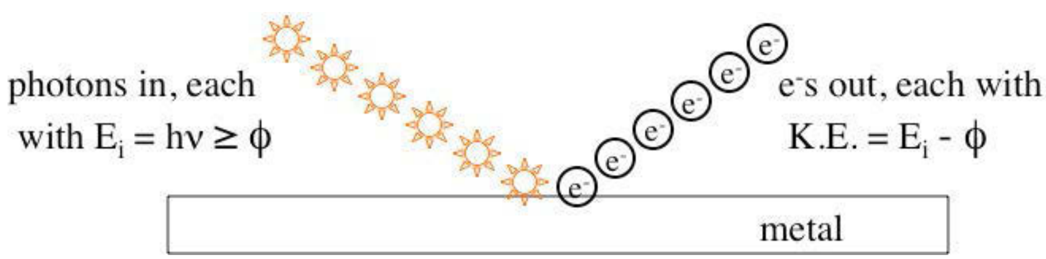
We can describe this mathematically:

K.E. = ________________ or **E_i** = ________________

(Note: these are just different forms of the equation $K.E = h\nu - h\nu_0$)

Let's try some example problems.

The # of electrons ejected from the surface of a metal is proportional to the ____________ of photons absorbed by the metal and not the energy of the photons (assuming $E_i \geq \phi$).



Thus, the **intensity** (I) of the light (energy/sec) is proportional to the # of photons absorbed/sec and the # of electrons emitted/ sec

Unit of intensity (I : W = __________

High intensity means more ________________ and NOT more ________________.

Understanding that light is made up of photons (it is quantized); that the energy of a photon is proportional to its frequency; and that intensity of light is measured in photons per sec, explains the experimental observations that could not be explained by classical physics.