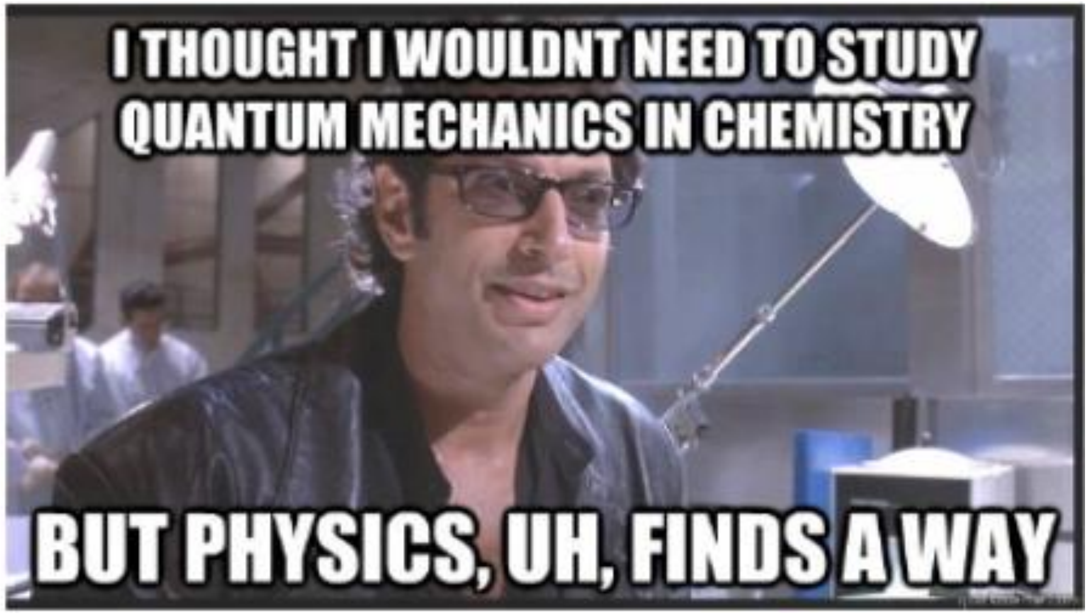
Atoms Lecture 1: Light and Matter

Learning Objective	Openstax 2e Chapter
Electromagnetic Radiation	6.1
Blackbody Radiation	6.1
Photoelectric Effect	6.1
Atomic Emission Spectra	6.1, 6.2

Suggested Practice Problems

Chapter 6 Exercises – Questions: 3, 5, 7, 9, 11, 15, 19, 23

Answers can be found in the Chapter 6 Answer Key



Classical Mechanics

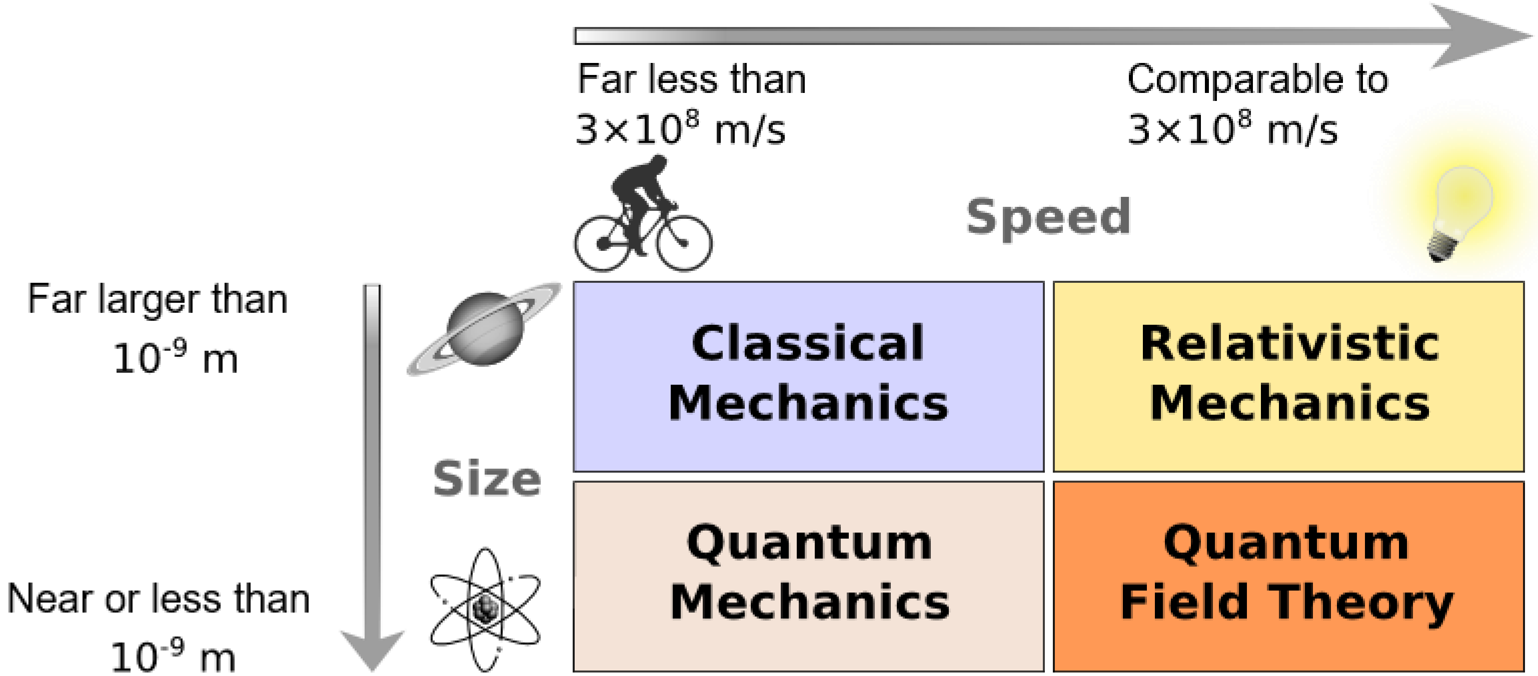
The physical theory describing the motion of macroscopic objects.

- Based on Newton's laws of motion.
- Interaction of forces and matter is described by
$$\vec{F} = m\vec{a}$$
- If we know an object's mass (m) and the force acting on it ($\vec{F}$), we can predict its acceleration ($\vec{a}$) and how it will move (determinism).
- At the end of 19th century, there were 3 experiments that classical mechanics couldn't explain which lead to the development of quantum theory.
    1) Black body radiation
    2) Photoelectric effect
    3) Atomic spectra

All 3 experiments involved the interaction of light and matter, so we first need to talk about waves.

Source: https://physics.aps.org/articles/v8/s111

But, why should we care?



Source: https://en.wikipedia.org/wiki/File:Modernphysicsfields.svg

- Interactions between electrons and nuclei lead to chemical bond formation
  - Bonding dictates the structure of molecules
  - Changes in bonding drive chemical reactions
- If we want to understand chemistry, we need to understand electrons. And, for that, we need to understand quantum mechanics.

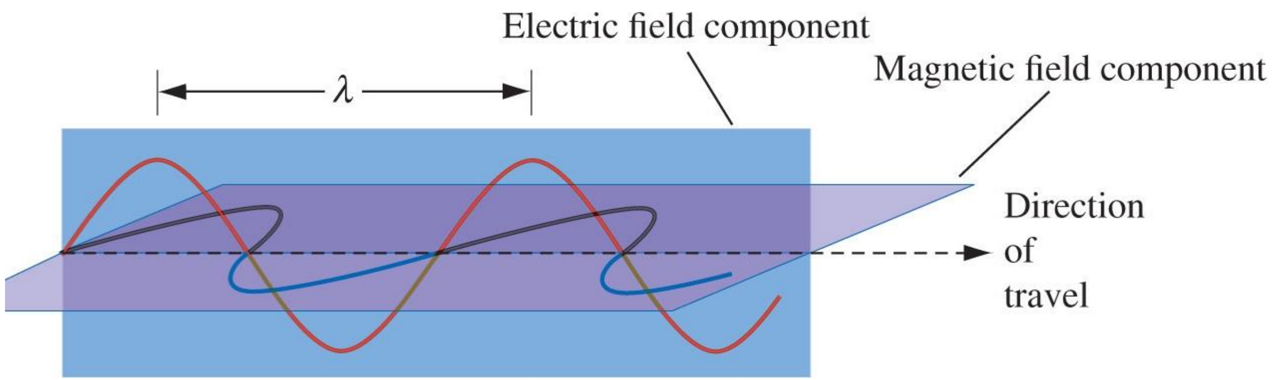
Electromagnetic Radiation

Examples includes visible light, x-rays, infrared, microwaves, …

Treat as a wave: Oscillation of electric (E) and magnetic (H) fields through space and matter

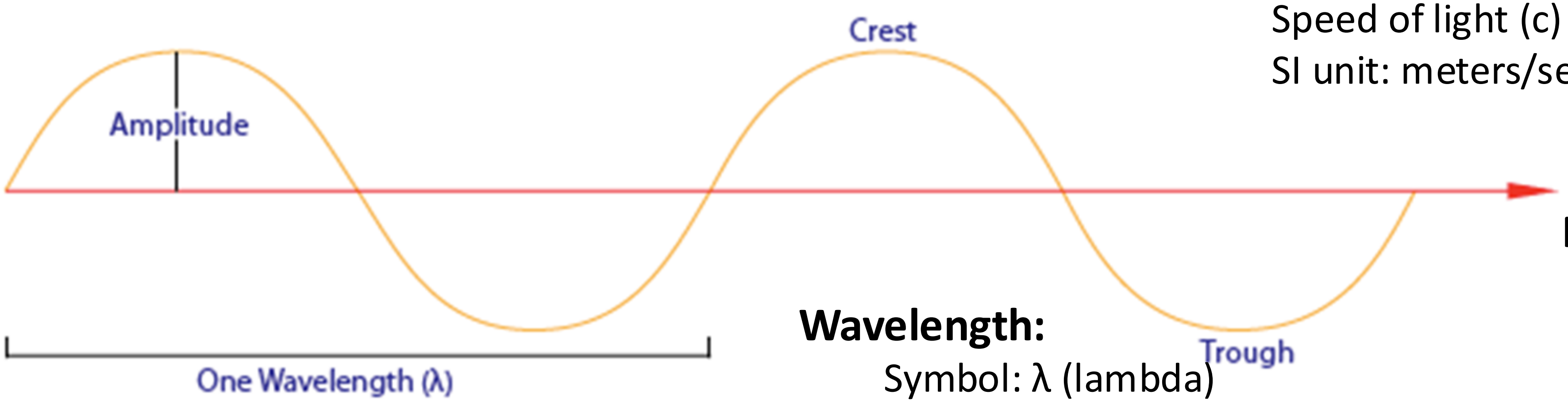
- E & H fields are perpendicular to each other
- E & H fields are in phase

We'll focus on the electric field to analyze EM waves characterized by:



$$\boxed{c = \lambda\, \nu}$$

Speed of light (c) = 2.9979 x 10^8 $m \cdot s^{-1}$ (in vacuum)
SI unit: meters/second ($m/s = m \cdot s^{-1}$)



Wavelength:

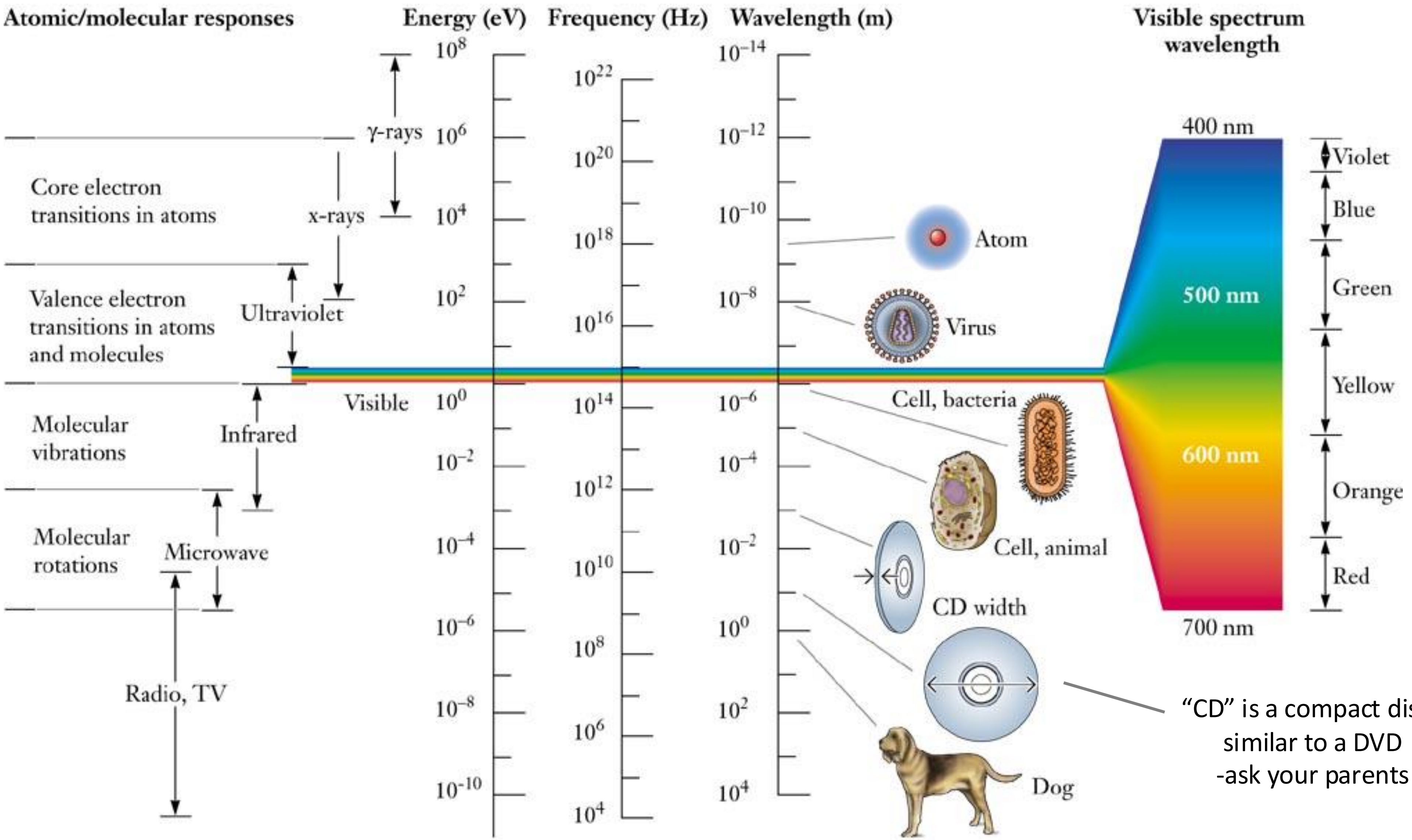
Symbol: λ (lambda)
SI unit: meters (m)

Frequency:

Symbol: ν (nu) [NOT VEE]
SI unit: Hertz or 1/seconds
(Hz = 1/s = s^{-1})

Electromagnetic Spectrum

Wavelength and frequency are inversely proportional

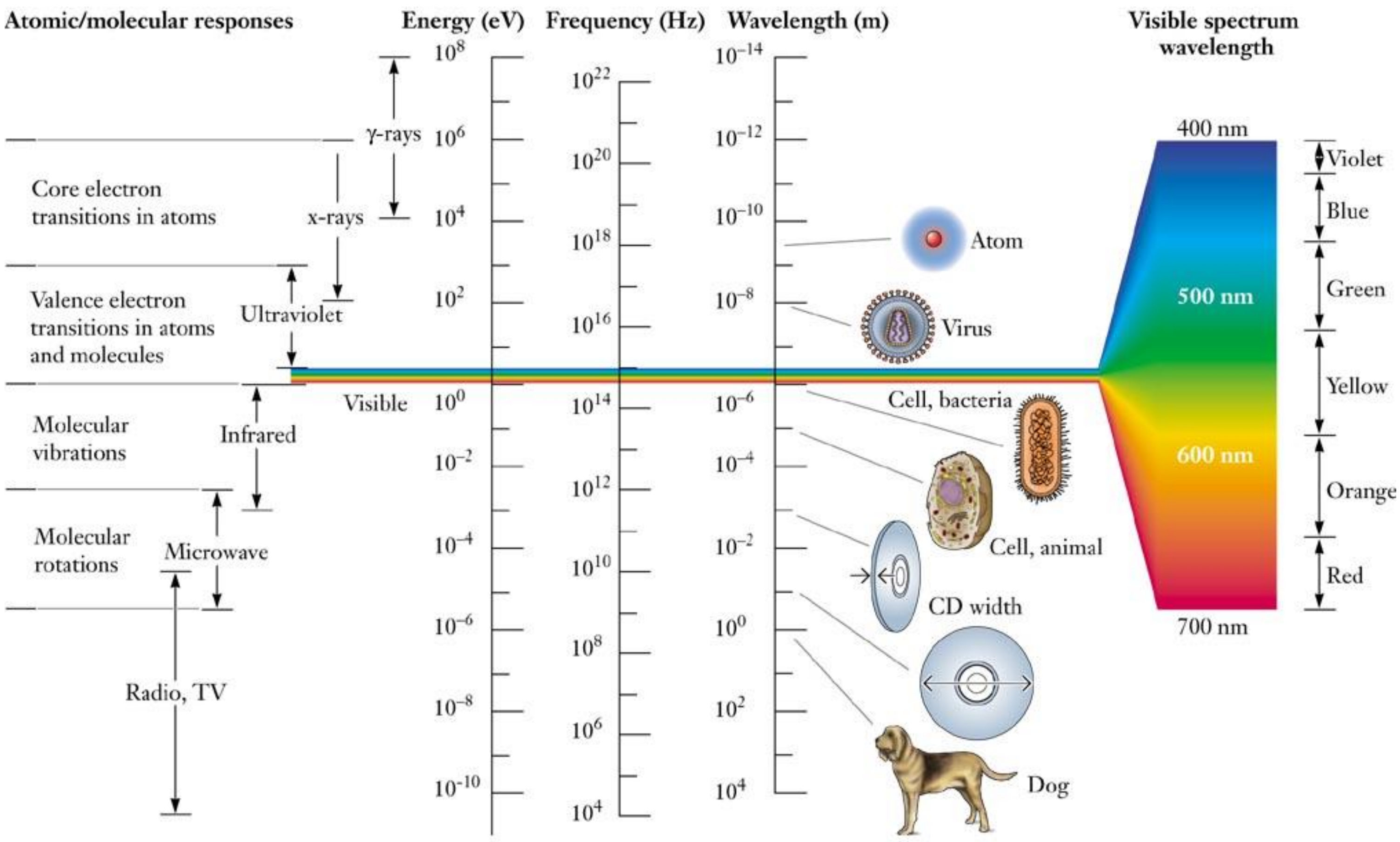


“CD” is a compact disk, similar to a DVD -ask your parents

Example

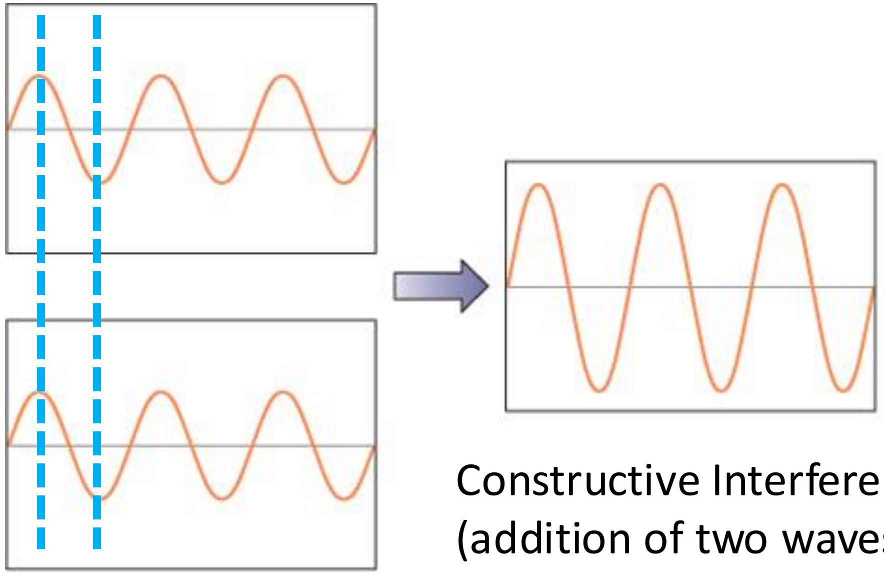
Based on the given diagram and equation which of the following statements is TRUE?

$$c = \lambda\,\upsilon$$



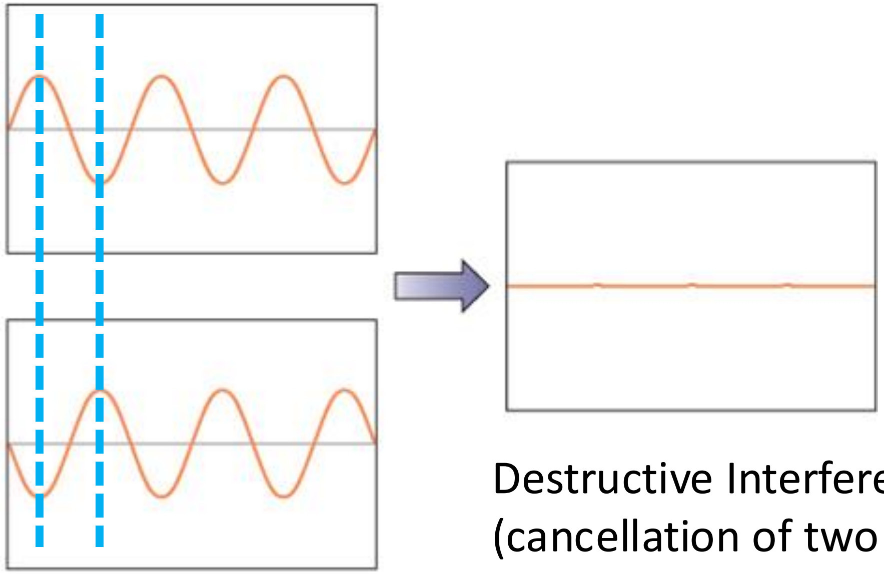
1. The wavelength of radio waves are *shorter* than the wavelength of visible waves.
2. The frequencies of ultraviolet waves are *greater* than the frequencies of infrared waves.
3. The energy of ultraviolet waves are *greater* than the energy of X-ray waves.
4. The gamma rays has the *smallest* frequencies and *largest* wavelengths.

Interference of Electromagnetic Waves



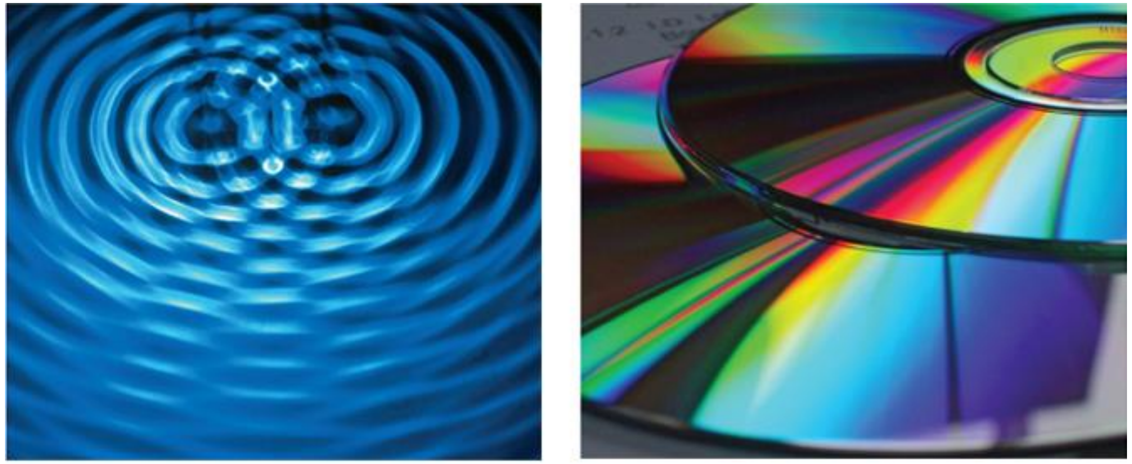
Constructive Interference
(addition of two waves)

(a)



Destructive Interference
(cancellation of two waves)

(b)



(a) (b)

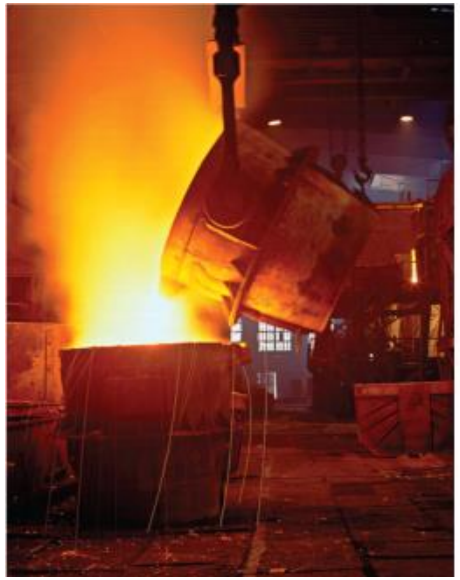
Examples of interference
(a) Stones and ripples
(b) CD/DVD reflection

Consistent with light behaving as a wave.

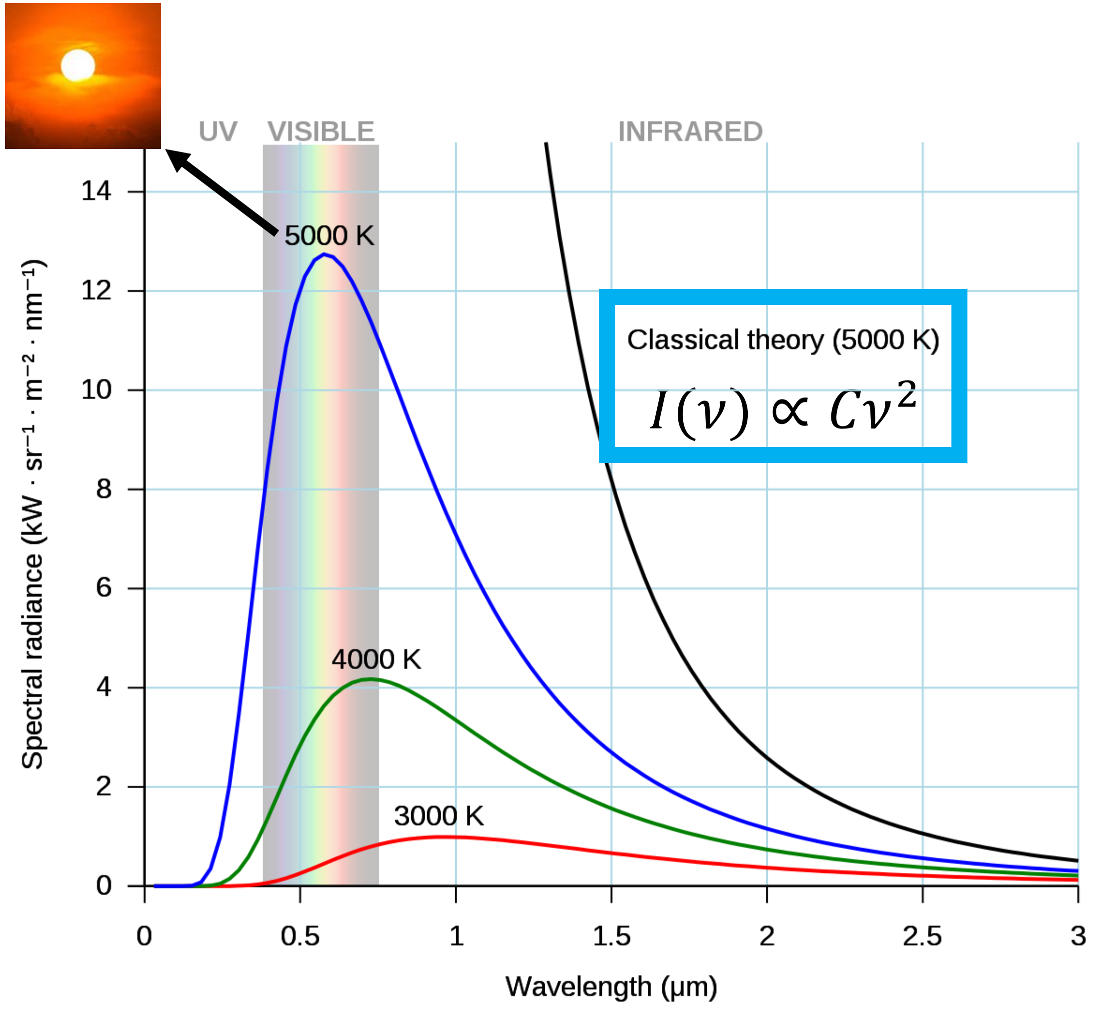
1) Black Body Radiation

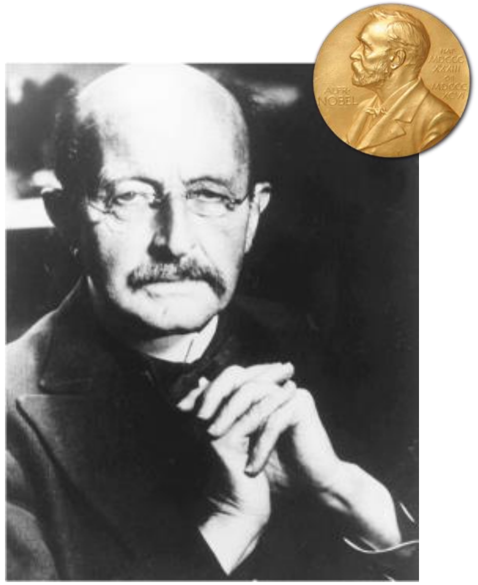
Classical physics could not provide a complete explanation of light emission by heated solids.

Electric-stove heating element



Molten Iron





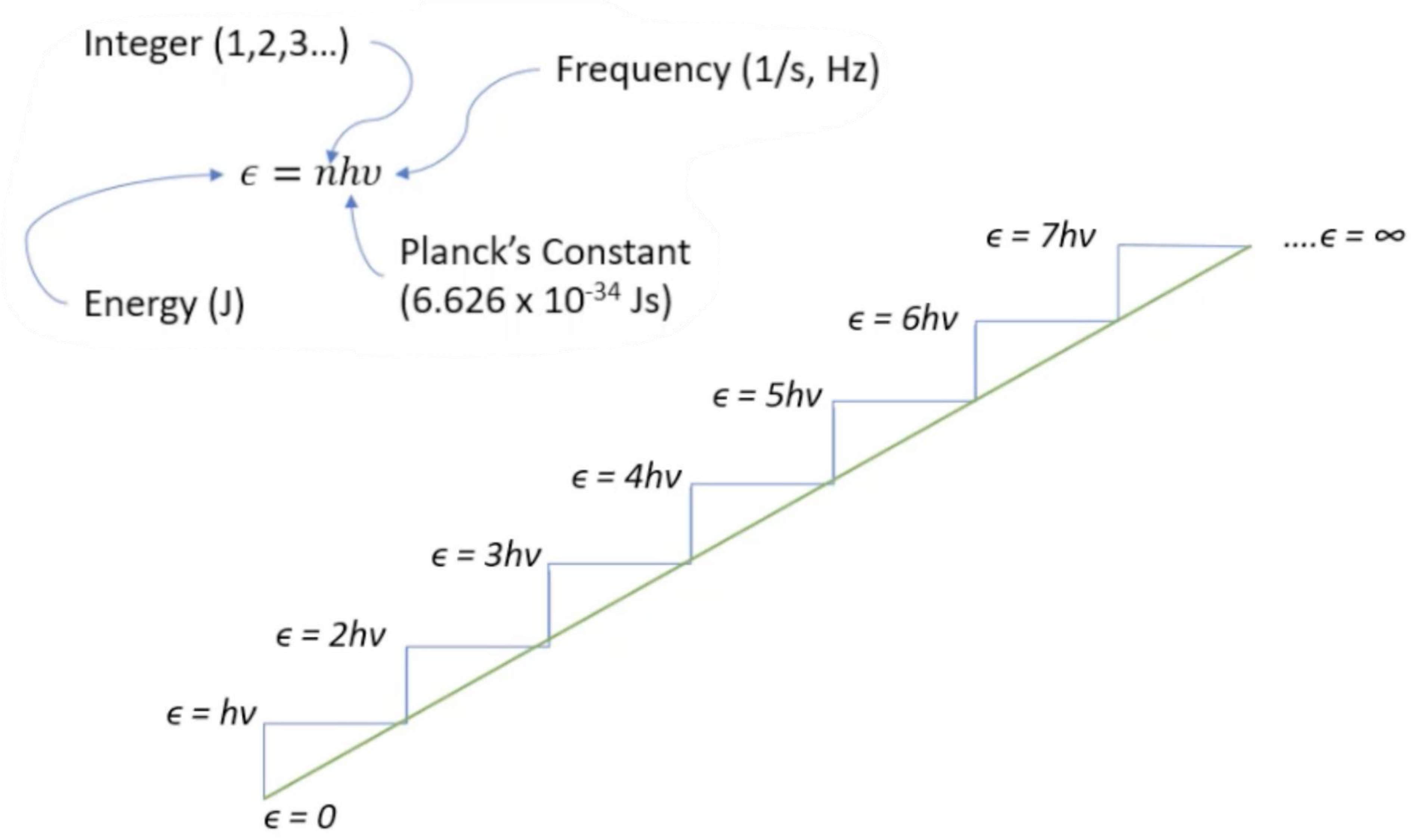
Max Planck, 1900

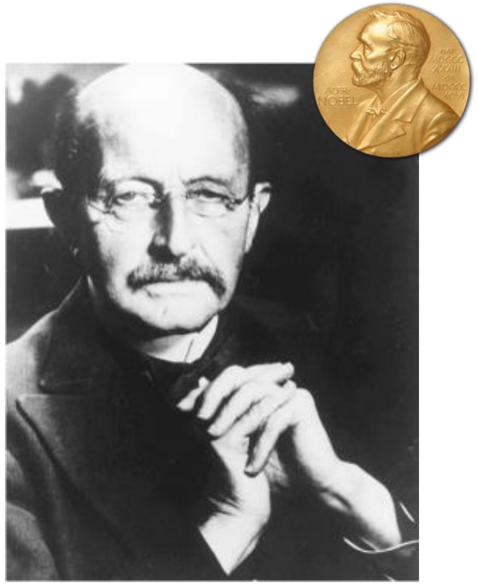
Energy, like matter, is discontinuous.

$$E = h\nu$$

1) Black Body Radiation

Energy is Quantized: System can only absorb or emit energy in discrete amounts called quanta.





Max Planck, 1900

Energy, like matter, is discontinuous.

$$E = h\nu$$

Example

Determine the energy, in joules, of radiation of frequency 7.39 x 10^{15} Hz.

<u>Physical constants:</u>
h = 6.626 × 10^{-34} J s

Given information: $\nu = 7.39 \times 10^{15}\ \mathrm{Hz}$

Compute energy using:

$$E = h\nu$$

$$E = (6.626 \times 10^{-34}\ Js) \times (7.39 \times 10^{15} s^{-1}) = 4.90 \times 10^{-18} J$$

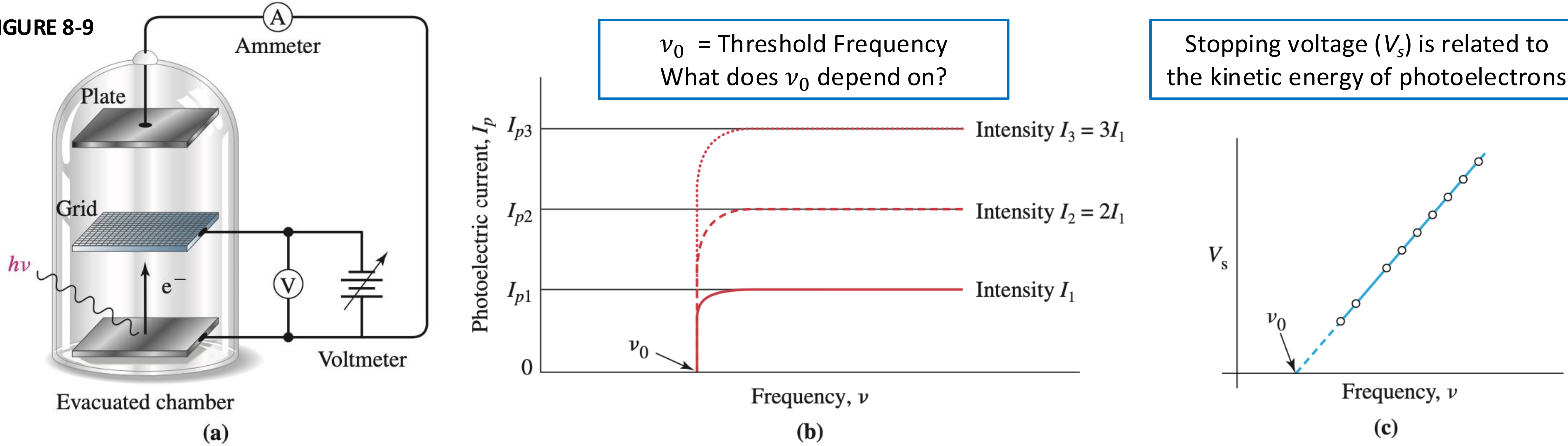
2) Photoelectric Effect

Classical wave theory could not explain the observations of the photoelectric effect.

FIGURE 8-9

ν_0 = Threshold Frequency
What does ν_0 depend on?

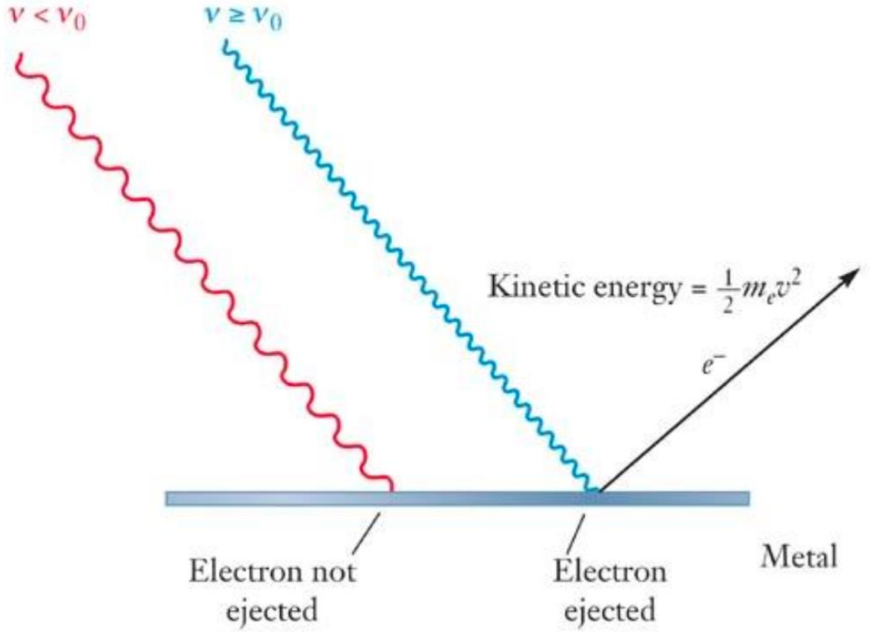
Stopping voltage (V_s) is related to the kinetic energy of photoelectrons



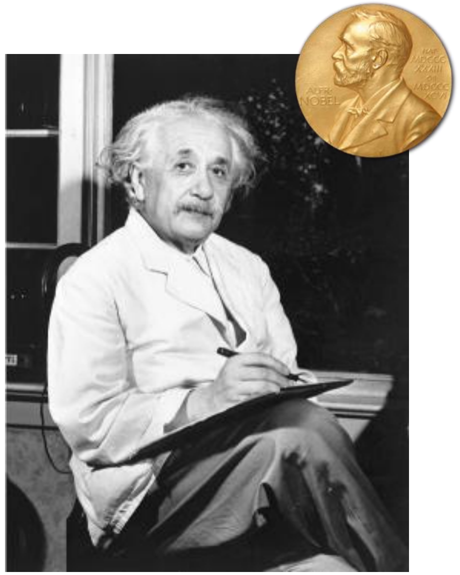
- Photoelectric Effect Phenomena: When light strikes the surface of certain metals, electrons are ejected.
- No matter how intense the light, no current flows if the $\nu_{light} < \nu_0$.
- For $\nu_{light} > \nu_0$ (there is a photoelectric current no matter how weak the light):
  - The # of electrons emitted (i.e., photoelectric current) depends only on the intensity of the light, but
  - The kinetic energies (i.e., velocity) of the emitted electrons depend only on the frequency of light.

2) Photoelectric Effect

Einstein showed that the observations are expected from a particle interpretation of radiation.



$$E_{\text{photon}} = \Phi + \text{K.E. electron}$$
$$h\nu = h\nu_0 + \frac{1}{2}m_e u^2$$



Albert Einstein, 1905

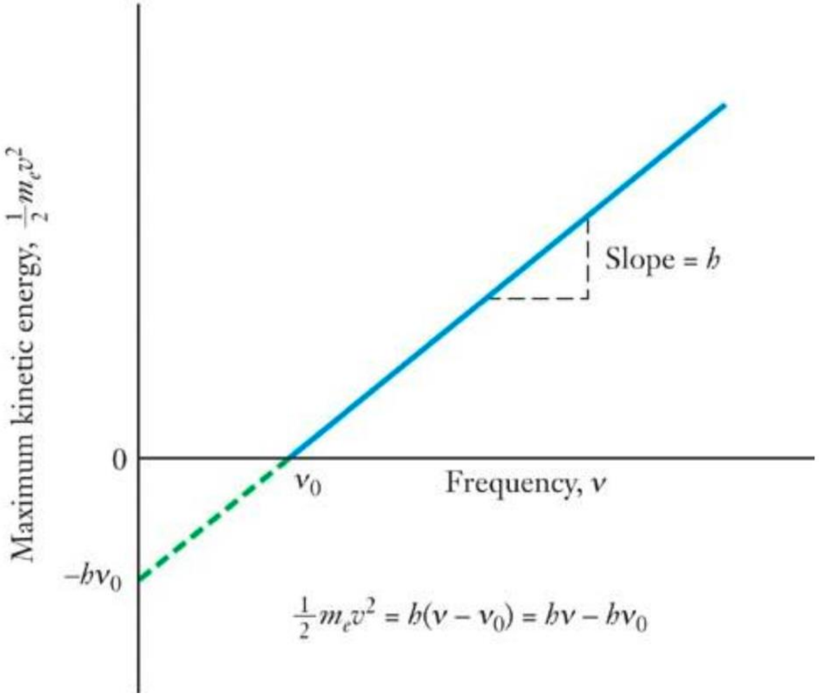
Electromagnetic radiation has particle-like properties.

$$E_{\text{photon}} = h\nu$$

- When a photon of energy $h\nu$ strikes a bound electron in the metal's surface:
  - A photoelectron is liberated if $h\nu_{light} > \Phi$, where Φ (work function) represents the minimum energy needed to extract an electron. So, it is related to threshold frequency ν_0 through $\Phi = h\nu_0$.
  - Any energy in excess of the work function appears as the kinetic energy (K.E.) of emitted photoelectron.

2) Photoelectric Effect

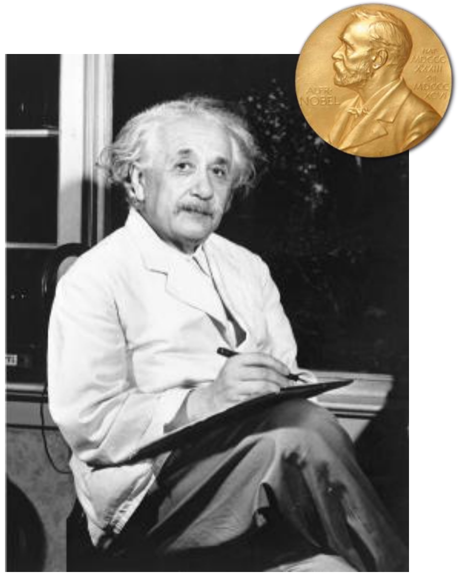
Einstein showed that the observations are expected from a particle interpretation of radiation.



charge of electron

$$\frac{1}{2}mu^2 = h(v - v_0) = \underset{\uparrow}{e}\, V_s$$

$$V_s \propto v_{light}$$



Albert Einstein, 1905

Electromagnetic radiation has particle-like properties.

$$E_{\text{photon}} = h\nu$$

- Experimental way to confirm Planck's constant (h).
- The negative potential on the grid acts to slow down the electrons.
  - Increasing the potential, a point is reached at which the photoelectrons are stopped. This is called **<u>stopping voltage</u>** (V_s). $= e\,V_s$
  - At the stopping voltage, the kinetic energy of photoelectrons has been converted to potential energy.

Example

The minimum energy required to cause the photoelectric effect in potassium metal is 3.69 x 10^{-19} J. If 420 nm radiation is shone on potassium, will electrons be ejected? If yes, what is their velocity?

Physical constants:
h = 6.626 × 10^{-34} J s (J = kg m^2 s^{-2})
m_e = 9.109 × 10^{-31} kg
c = 2.9979 × 10^8 m s^{-1}

Given information:

$$\Phi = 3.69 \times 10^{-19} J$$
$$\lambda_{photon} = 420\, nm$$

First, calculate the energy of a single photon:

$$E = h\nu \qquad and \qquad c = \lambda\nu$$

$$E_{photon} = h\nu = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34}\, Js) \times (2.9979 \times 10^{8} ms^{-1})}{4.2 \times 10^{-7} m} = 4.7 \times 10^{-19} J$$

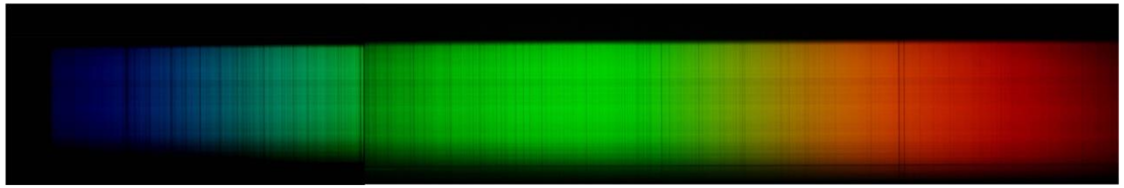
The electrons are ejected, because E_{photon} > 3.69 x 10^{-19} J. To calculate their velocity:

$$E_{EM} = \Phi + \frac{1}{2} mu^2$$

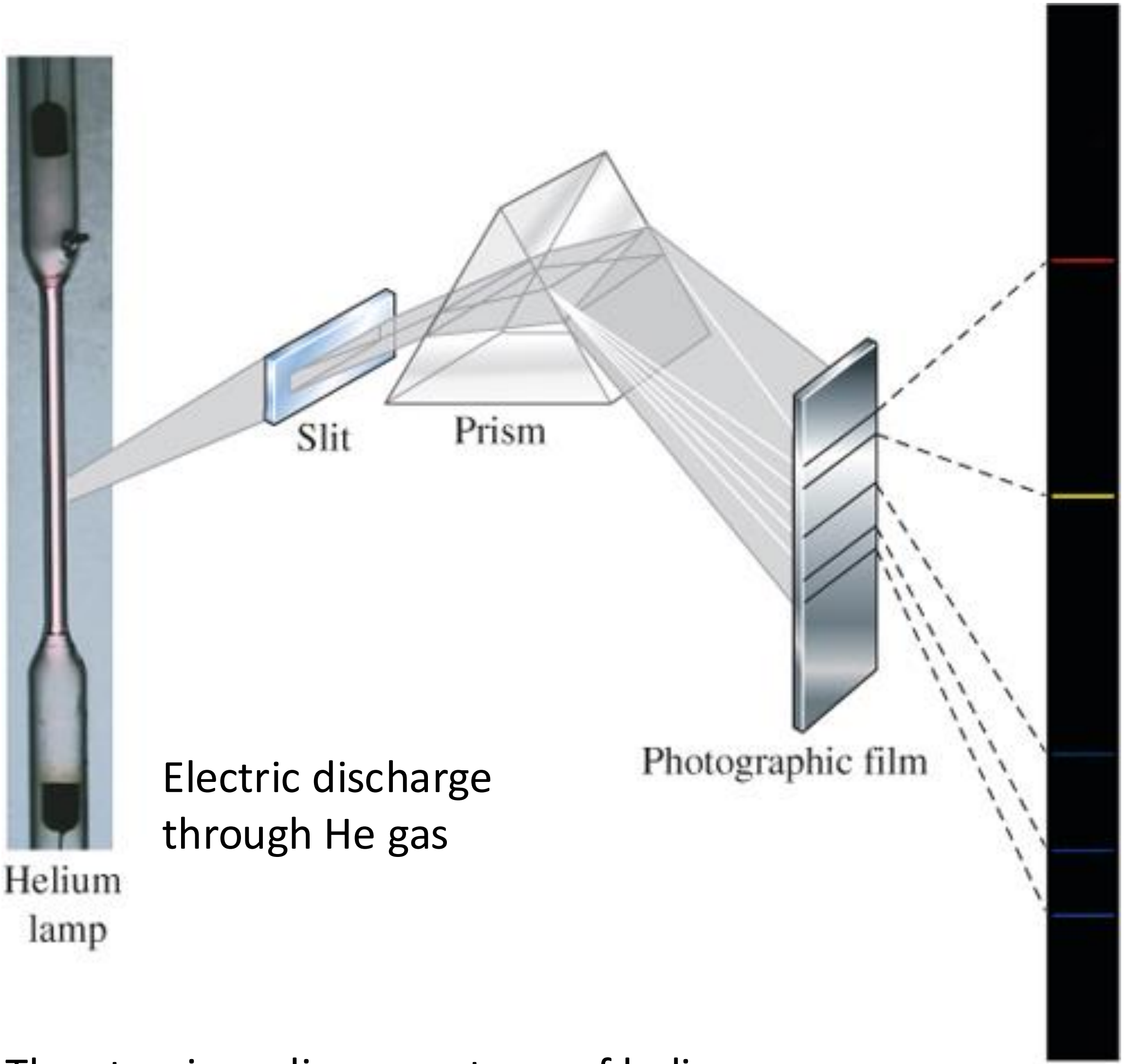
$$4.7 \times 10^{-19} J = 3.69 \times 10^{-19} J + \frac{1}{2}(9.109 \times 10^{-31} kg)u^2 \longrightarrow \boxed{u = 4.8 \times 10^{5} ms^{-1}}$$

3) Atomic Emission Spectra

Newton's (1667) experiment showed the sunlight spectrum with a prism



Josef Fraunhofer (1814) discovered that the sunlight spectrum contains missing lines.



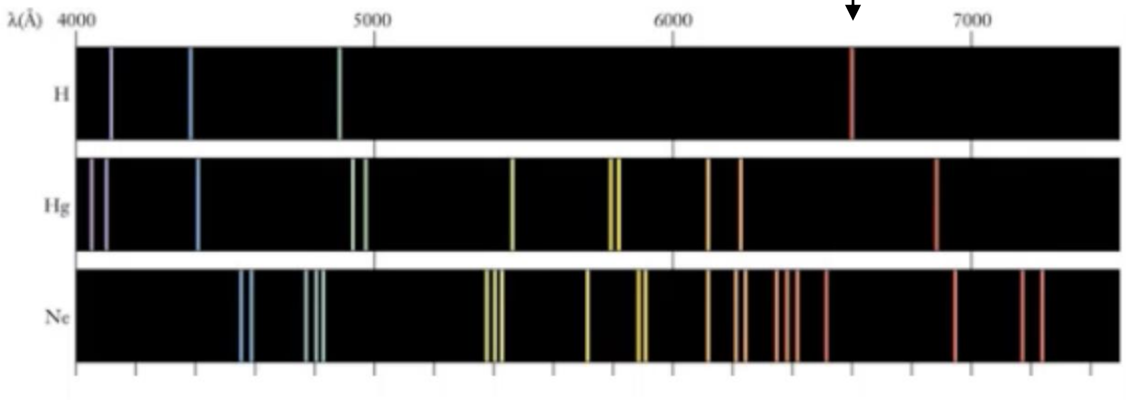
Electric discharge through He gas

The atomic, or line, spectrum of helium

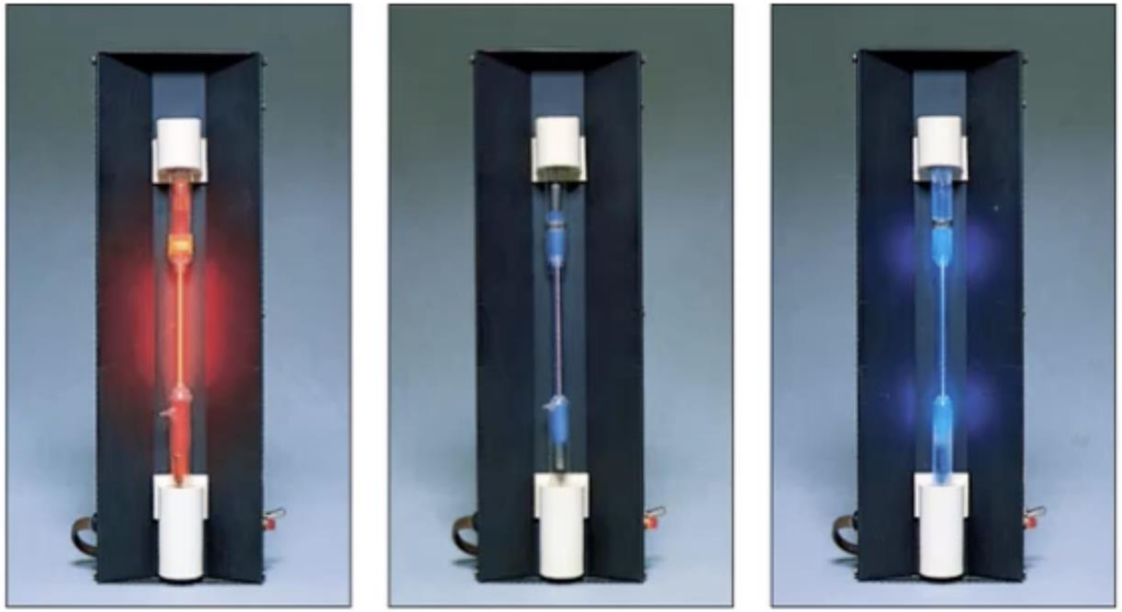
3) Atomic Emission Spectra

If we heat up atoms, they emit light… but only at discrete frequencies (characteristic spectrum).

Famous Hα line



Hydrogen Neon Mercury



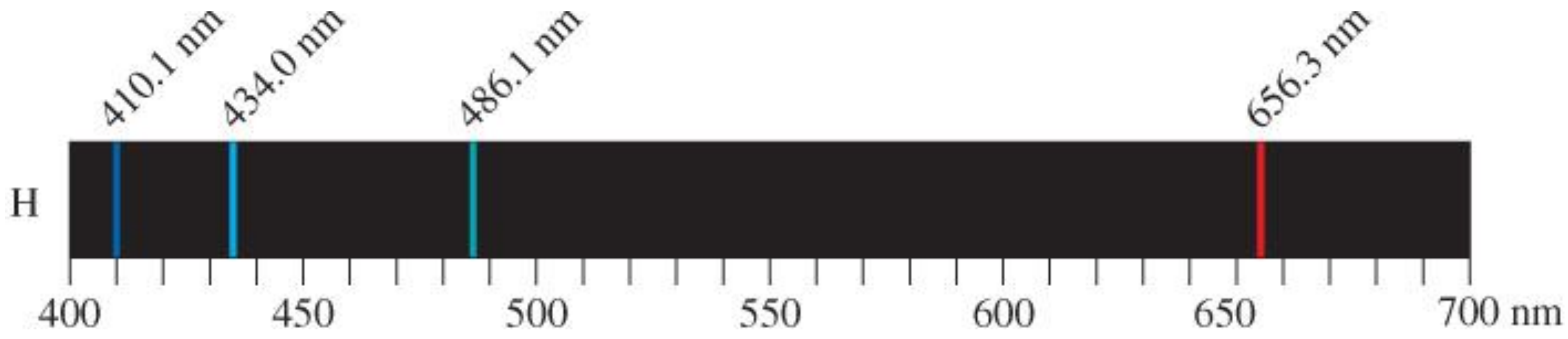
- Atomic line spectra are discontinuous.
- Each element has its own distinctive line spectrum – kind of like an atomic fingerprint.

The North America Nebula, June 6, 1996

NASA Astronomy Picture of the Day (http://antwrp.gsfc.nasa.gov/apod/)

3) Atomic Emission Spectra

Atomic spectrum of Hydrogen atom is among the most extensively studied.



The Balmer series for hydrogen atoms – a line spectrum (only ones visible)

Niels Bohr, 1913

Johan Balmer (1885)

$$\lambda = \frac{Bm^2}{m^2 - n^2}$$

B is a constant
n and m are integers

Johannes Rydberg (1888)

$$\frac{1}{\lambda} = \frac{4}{B}\left(\frac{1}{n^2} - \frac{1}{m^2}\right) = R_H\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

Rydberg Constant = $1.097 \times 10^7\ m^{-1}$

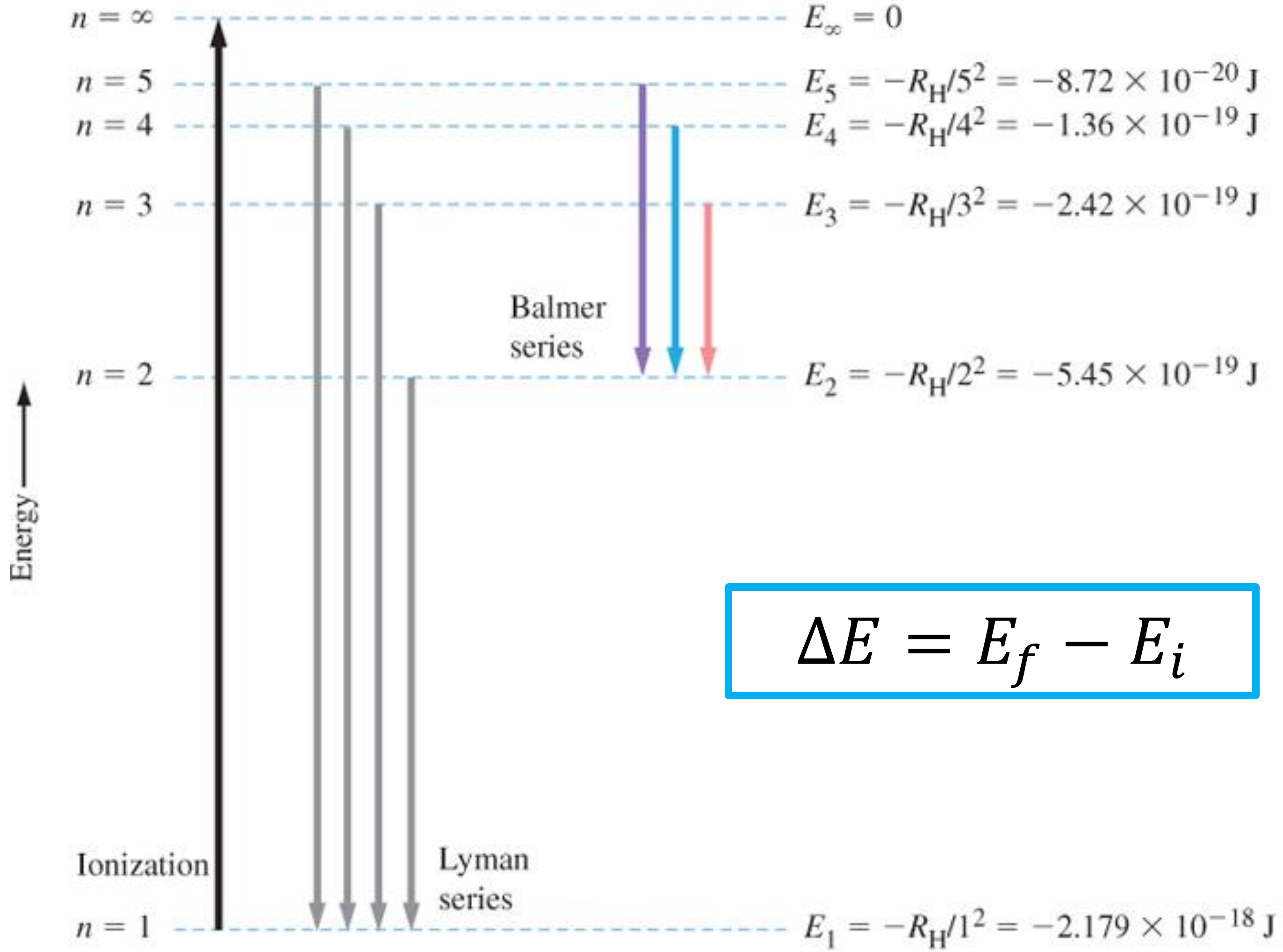
$$E_n = \frac{-R_H}{n^2}$$

$n = 1, 2, 3, \ldots$
$R_H = 2.179 \times 10^{-18}$ J

3) Atomic Emission Spectra

For free proton and electron, set to E = 0, electron bound to proton has lower energy from there

The energy of H atom is quantized and all allowed energy values are negative.



$$\boxed{\Delta E = E_f - E_i}$$

Energy-level diagram for the hydrogen atom

Niels Bohr, 1913

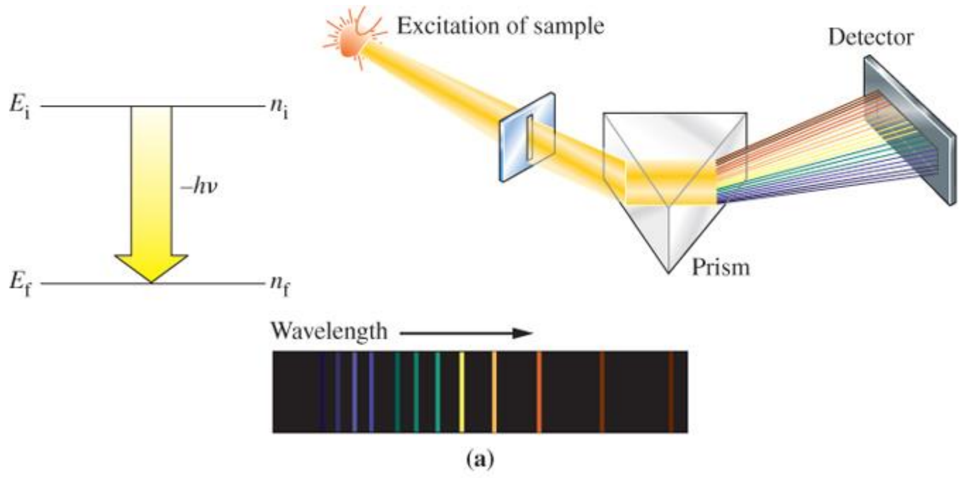
$$E_n = \frac{-R_H}{n^2}$$

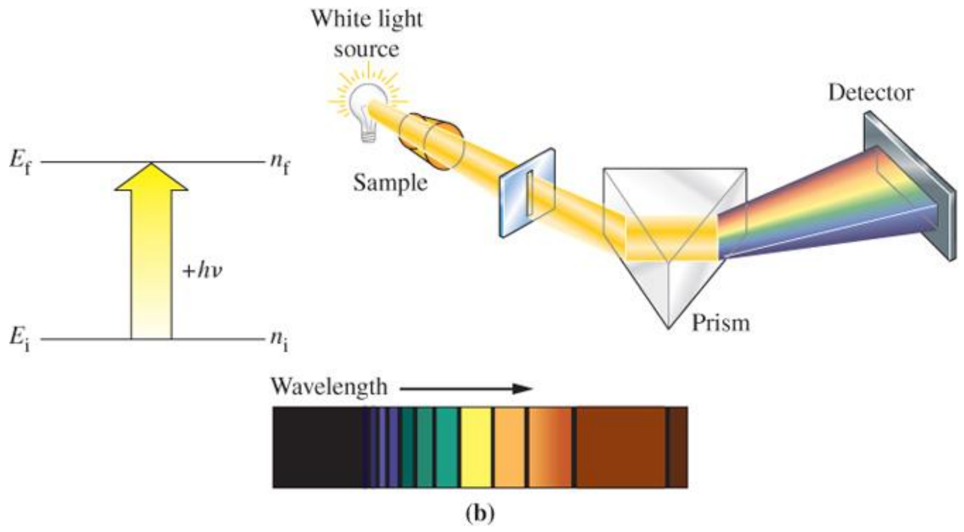
$$n = 1, 2, 3, \ldots$$

$$R_H = 2.179 \times 10^{-18}\ \text{J}$$

3) Atomic Emission Spectra

Radiation is emitted or absorbed by a transition of the electron from one quantum state to another.





Emission and absorption spectroscopy

$$\Delta E = E_f - E_i$$

$$\Delta E = -\mathrm{R}_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

and,

$$\Delta E = E_{photon} = h\,v$$

gives

$$\boxed{v = \frac{E_f - E_i}{h}}$$

Niels Bohr, 1913

$$E_n = \frac{-\mathrm{R}_H}{n^2}$$

$n = 1, 2, 3, \ldots$

$\mathrm{R}_H = 2.179 \times 10^{-18}$ J

Example

Determine the wavelength of light absorbed in an electron transition from n=3 to n=5 in a hydrogen atom.

Physical constants:

h = 6.626 × 10^{-34} J s (J = kg m^2 s^{-2})

c = 2.9979 × 10^8 m s^{-1}

R_H = 2.17868 × 10^{-18} J

Given information: $n_i = 3$

$n_f = 5$

First, calculate the energy absorbed:

$$\Delta E = -\mathrm{R}_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = -(2.17868 \times 10^{-18} J)\left(\frac{1}{25} - \frac{1}{9}\right) = 1.54928 \times 10^{-19} J$$

Then, calculate the wavelength:

$$\Delta E = h\,v = \frac{hc}{\lambda} \rightarrow \lambda = \frac{(6.626 \times 10^{-34} Js)(2.9979 \times 10^{8} m/s)}{1.54928 \times 10^{-19} J} = 1.282 \times 10^{-6} m = 1282\,nm$$