Chapter 38
Photons, Electrons, and Atoms

1. Emission and absorption of light
2. The photoelectric effect
3. Atomic line spectra and energy levels
4. The nuclear atom
5. The Bohr model
6. The laser
7. X-Ray production and scattering
8. Continuous spectra
9. Wave-particle duality

Dual nature of light

- **Wave-like behavior** in phenomena such as
  - Interference
  - Diffraction
  - Polarization
- **Particle-like or quantum** behavior in phenomena such as
  - Emission
  - Absorption
  - Scattering
  - Production of line spectra by atoms, photoelectric effect & x-ray
- **Electromagnetic field (wave) is quantized** and the quantum of energy is called a **photon**. Energy of the elementary particles in the atom (electrons, protons, etc.) is also quantized.
- Together these quantization concepts are base for the **quantum mechanics or quantum physics**.

Line spectra

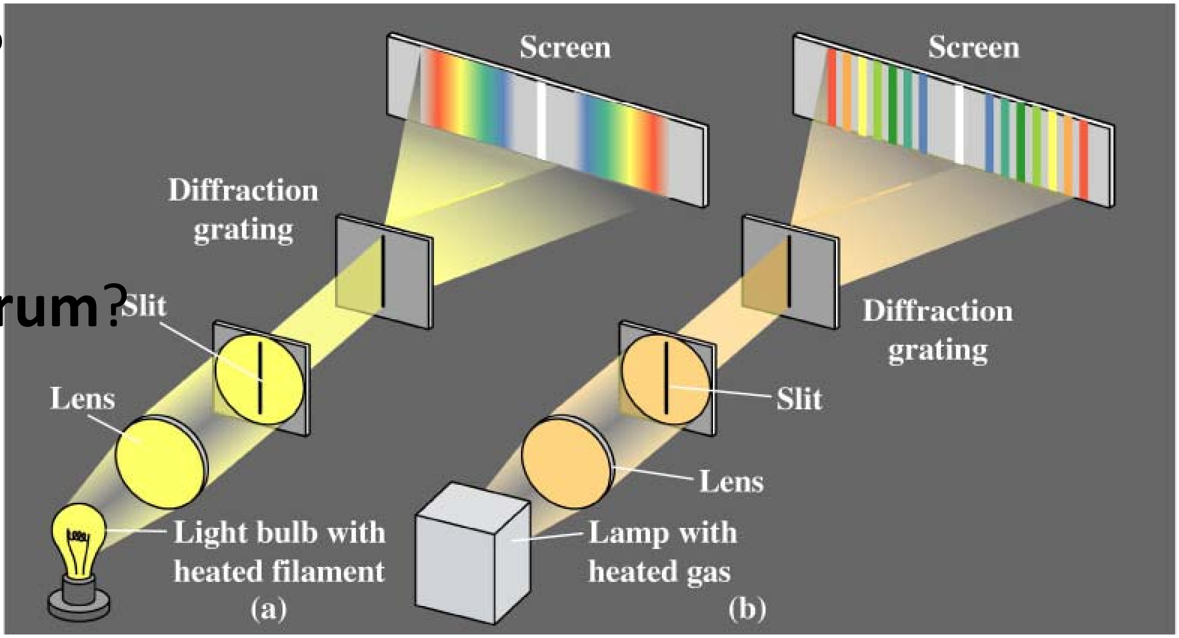
- Hertz generated electromagnetic waves of 10^8 HZ using resonating LC circuits (Ch32).
- What is frequency of visible light? Can we generate those frequencies using electronics?
- How else we can generate visible light?
- What is going on inside a material in fire? Or in a light bulb?
- Why each element

has a unique spectrum?

- What is in **internal**

structure of an atom to

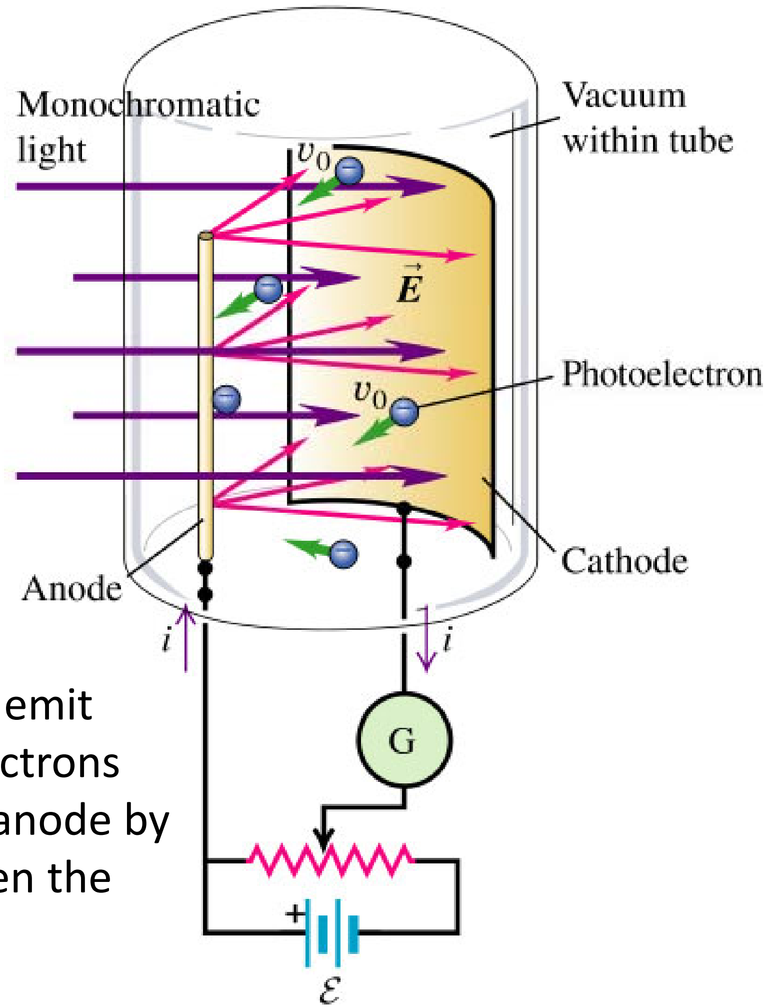
generate such an spectrum?



More puzzling phenomena

- **X-rays** (1895) produced in high voltage electric discharge tubes
  - What produced them?
  - What determines their very short wavelength (high energy)?
  - Why they can penetrate deep into most of the material?
- **Photo-electric effect**: emission of electrons when light strikes a surface.
  - What is the correlation between the color of the light and kinetic energy of the escaped electron and the surface (material)?
  - Why some light can generate photoelectrons from a surface and some can't?
  - Why a given light can generate photoelectrons from one surface but not the other one? (read pages 1309-1312 to appreciate the scientific method)

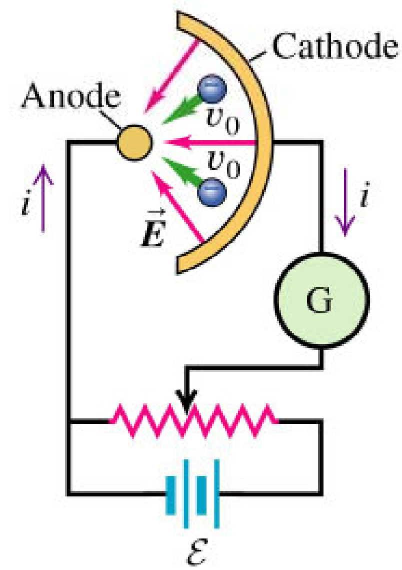
Apparatus for observing the photoelectric effect



(a)

Light causes cathode to emit photoelectrons. The electrons are driven towards the anode by the electric field between the cathode and anode.

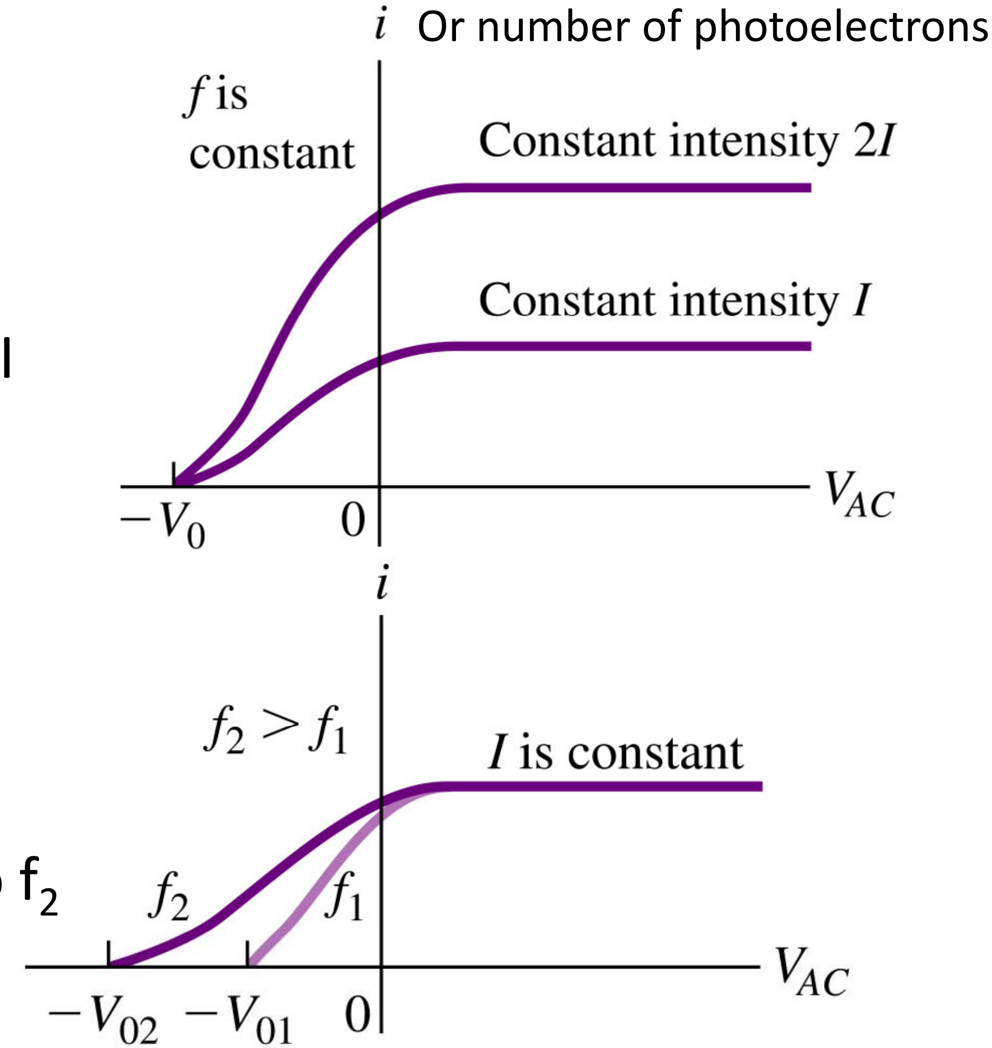
Some electrons reach the anode even with the direction of the electric field reversed



(b) Overhead view with $\vec{E}$ field reversed

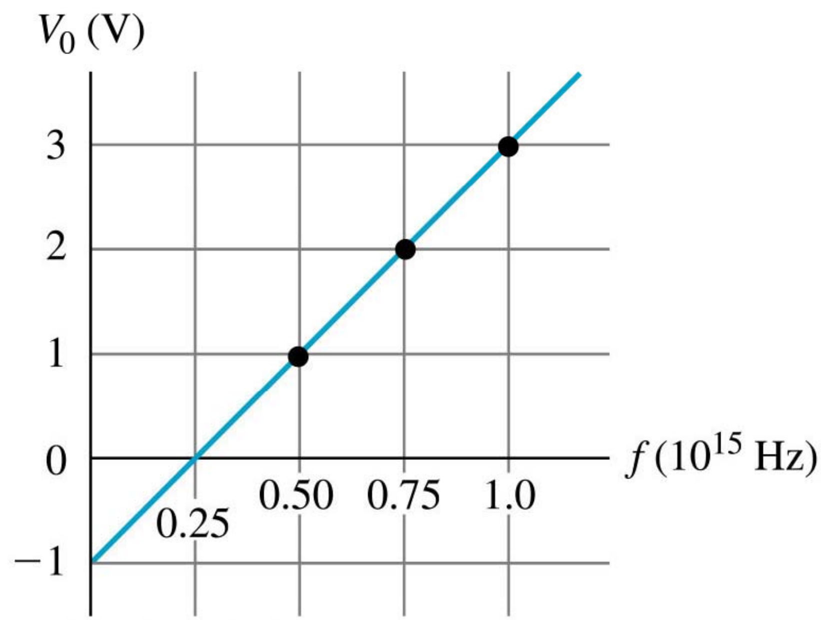
Stopping potential and maximum kinetic energy of photoelectrons

- Experiment 1
  - Light of frequency f and intensity I
  - Double the intensity to 2I without changing the frequency
- Experiment 2
  - Light of intensity I and frequency f_1
  - Double the frequency to f_2 without changing the intensity



Stopping potential and frequency of the incident light

- Experiment 3
  - Light of intensity I and frequency f. Find the stopping potential.
  - Decrease the frequency find the stopping potential.
  - Decrease the frequency until no photoelectron is emitted.
  - Plot the stopping potentials vs. frequency



Let's construct a model

I have a photon (quantum of light) with energy E arriving at a surface with work function ϕ, energy required to detach an electron from the surface.

Case 1: $E < \phi$ No photoelectron is generated.

Case 2: $E \geq \phi$ Photon deposites its energy on the electron.The electron escapes the surface with some kinetic energy greater than zero. $E = \phi + mv^2/2$

Now if I apply reverse voltage, V_0 to stop the most energetic electron. The work used to stop the elctron is $-eV_0 = -\frac{1}{2}mv_{\max}{}^2 \rightarrow \boxed{K_{\max} = eV_0 = \frac{1}{2}mv_{\max}{}^2}$

We see plot of V_0 vs. f is a line such as $V_0 = a + bf$ This suggests that:

$$E = \phi + \frac{1}{2}mv^2 = \phi + eV_0 = \underbrace{\phi + e(a}_{\text{Independent of f}} + bf) \rightarrow E \propto f \rightarrow \boxed{E = hf}$$

*W*e can use experimental methods to measure the constant of proportionality h?

How do you find value of h? Suggest an experiment.

$\boxed{h = 6.6260693 \times 10^{-34} J.s = 4.136 \times 10^{-15} eV}$ where $\boxed{1eV = 1.602 \times 10^{-19} J}$

$1eV$ is energy gained by an electron moving through a $1V$ potential difference.

Einstein’s photon explanation

Albert Einstein got the Nobel prize for explanation of the photoelectric effect in 1905.

Since intensity of an EM wave is independent of frequency several things did not make sense with classical mechanics.

1) Existance of threshold frequency for the PE effect.

2) Independence of stopping potential from intensity & its dependence on the frequency.

3) Immediacy: even at very low intensities we don't have to wait for the PE effect to start if the frequency is above the threshold.

Based on Max Planck's work in 1900 Einstein postulated: a beam of light consists of small packages or quanta of energy called photons. Energy of each photon = constant $\times$ frequency

$$\boxed{E = hf = h\frac{c}{\lambda} \text{ where } h = 6.6260693(11)\times10^{-34}\ j.s}$$

then energy of photon in photoelectric effect is devided to overcome the work function of the suurface and kinetic energy of the electron released.

$$\boxed{hf - \phi = K_{\max} = \frac{1}{2}mv_{\max}{}^2 = eV_0}$$

Photon momentum

Concept of quantization of EM waves requires assignment of particle properties to them. Each photon has energy of

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

Particles with energy also have momentum.

Using the relativistic momentum formula $p = m\gamma v$ does not make sense with $v = c$.

But if we assume photon has zero rest mass or zero rest energy $\mathrm{E}_0 = 0$ then:

$$E^2 - E_0{}^2 = p^2c^2$$

Leads to a value for momentum of a photon.

$$\left.\begin{array}{l} E = pc \\ E = hf = h\dfrac{c}{\lambda} \end{array}\right\} = \boxed{p = \frac{h}{\lambda} = \frac{hf}{c}}$$

And the direction of the momentum is direction of the EM wave motion.

Examples

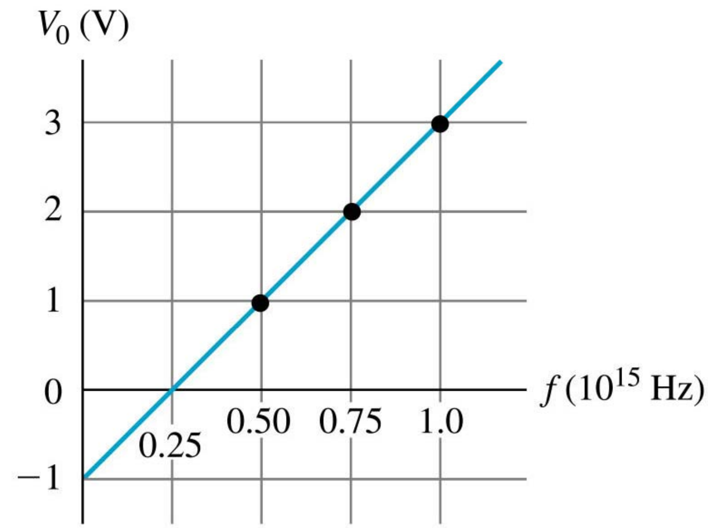
- Find the maximum kinetic energy and maximum speed of the electrons emitted in a photoelectric experiment where the potential to stop the electrons was 1.2V.
- What is the magnitude of the energy and momentum of each photon and total number of photons broadcasted from KQED at 89.5 Hz with a power of 43.0KW?

Determining work function and Planck's constant experimentally

- Using one cathode material and different light frequencies. Using different cathodes and one frequency. Any other way?

Identify: Find V_0 as a function of f.

Set up: find slope and intercept of the V_0 vs. f graph.



$$V_0 = \underbrace{\frac{\mathrm{h}}{\mathrm{e}}}_{\text{Slope}} f \underbrace{-\frac{\phi}{e}}_{\text{Intercept}}$$

$$-\frac{\phi}{e} = -1.0V \rightarrow \phi = 1.0eV = 1.6\times10^{-19}\,J$$

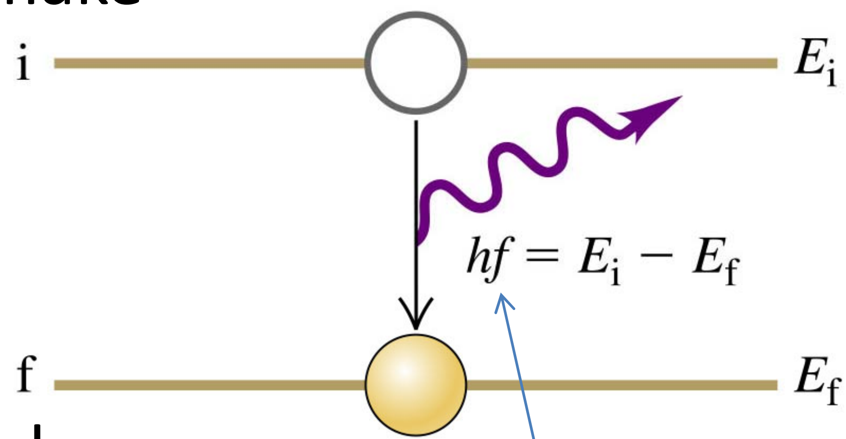
$$Slope = \frac{\Delta V_0}{\Delta f} = \frac{3.0V-(-1.0V)}{1.00\times10^{15}s^{-1}-0} = 4.00\times10^{-15}\,J.s/C = \frac{\mathrm{h}}{\mathrm{e}}$$

$$h = slope\times e = \left(4.00\times10^{-15}\,J.s/C\right)\times\left(1.60\times10^{-19}\,C\right)$$

$$h = 6.4\times10^{-34}\,J.s$$

Emission of photon by atoms

- Two concepts necessary to make sense of the line spectra:
  - Photon concept
  - Energy levels
- Example: calculate energy difference between the initial and final states of a krypton atom that emits a photon of wavelength 606 nm.



Energy of the emitted photon

$$E_i - E_f = hf = \frac{hc}{\lambda} = \frac{\left(6.63\times10^{-34}\,J.s\right)\left(3.00\times10^{8}\,m/s\right)}{606\times100^{-9}\,m}$$

$$\Delta E = 3.28\times10^{-19}\,J = 2.05eV$$

The hydrogen spectrum

In a electric discharge tube hydrogn gas emits the spectral lines below (well studied by 1913).

Balmer (1885) found that the spectral lines' wavelength all satisfy the Balmer's formula:

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \text{ where } n = 3, 4, 5, \ldots$$

$R = 1.097 \times 10^7 m^{-1}$ is the Rydberg constant (experimentally found to fit the lines)

We can calculate energy of the emitted photons & find energy of the atom before and after emission: $E = \frac{hc}{\lambda} = hcR\left(\frac{1}{2^2} - \frac{1}{n^2}\right) = E_i - E_f \rightarrow \underbrace{E_i = -\frac{hcR}{n^2}}_{\text{Excited state energy}}$ and $\underbrace{E_f = -\frac{hcR}{2^2}}_{\text{Ground state energy}}$

This suggests that the Hydrogen atom has energy levels of E_n given by:

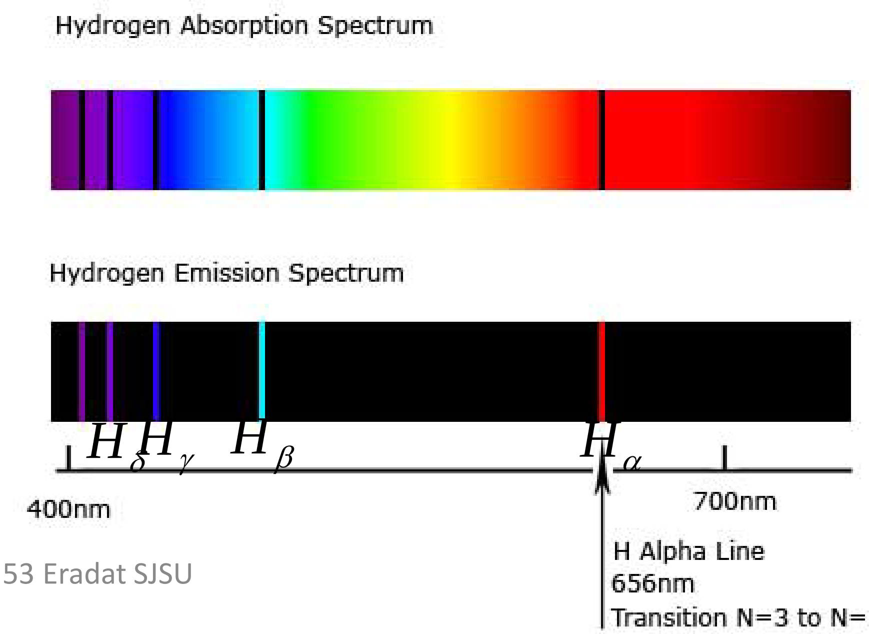
$$\boxed{E_n = \frac{hcR}{n^2} \qquad n = 1, 2, 3, \ldots}$$

$$\boxed{hcR = 2.179 \times 10^{-18} J = 13.6 eV}$$

What do you think of these numbers?

$E_1 = -13.6 eV,\ E_2 = -3.40 eV,$

$E_3 = -1.51 eV,\ E_4 = -0.85 eV, \ldots$



Hydrogen Series

Other spectral series for the hydrogen aton named after their discoverers:

Lyman series (UV) $\quad \frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right) \qquad n = 2, 3, 4, 5, \ldots$

Balmer (VIS) $\quad \frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad n = 2, 3, 4, 5, \ldots$

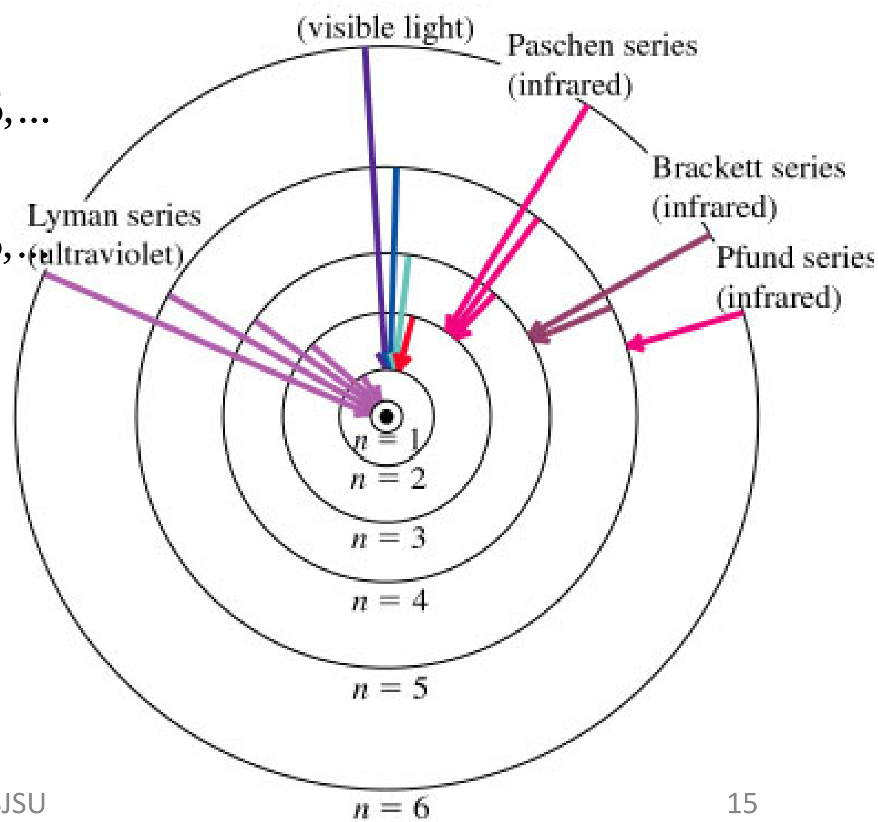
Paschen series (IR) $\quad \frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right) \qquad n = 2, 3, 4, 5, \ldots$

Brackett series (IR) $\quad \frac{1}{\lambda} = R\left(\frac{1}{4^2} - \frac{1}{n^2}\right) \qquad n = 2, 3, 4, 5, \ldots$

Pfund series (IR) $\quad \frac{1}{\lambda} = R\left(\frac{1}{5^2} - \frac{1}{n^2}\right) \qquad n = 2, 3, 4, 5, \ldots$

$$\boxed{E_n = \frac{hcR}{n^2} \qquad n = 1, 2, 3, \ldots}$$

$$\boxed{hcR = 2.179 \times 10^{-18}\, J = 13.6 eV}$$



(a)

Hydrogen Series

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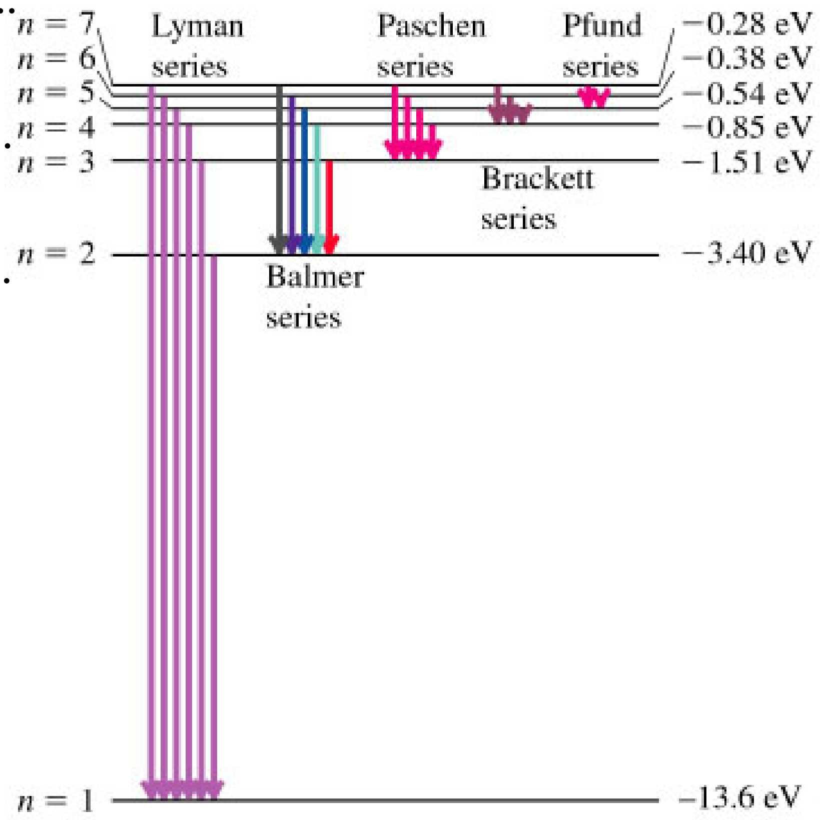
$$\boxed{E_n = \frac{hcR}{n^2} \qquad n = 1,2,3,\ldots}$$

$$\boxed{hcR = 2.179 \times 10^{-18} J = 13.6 eV}$$

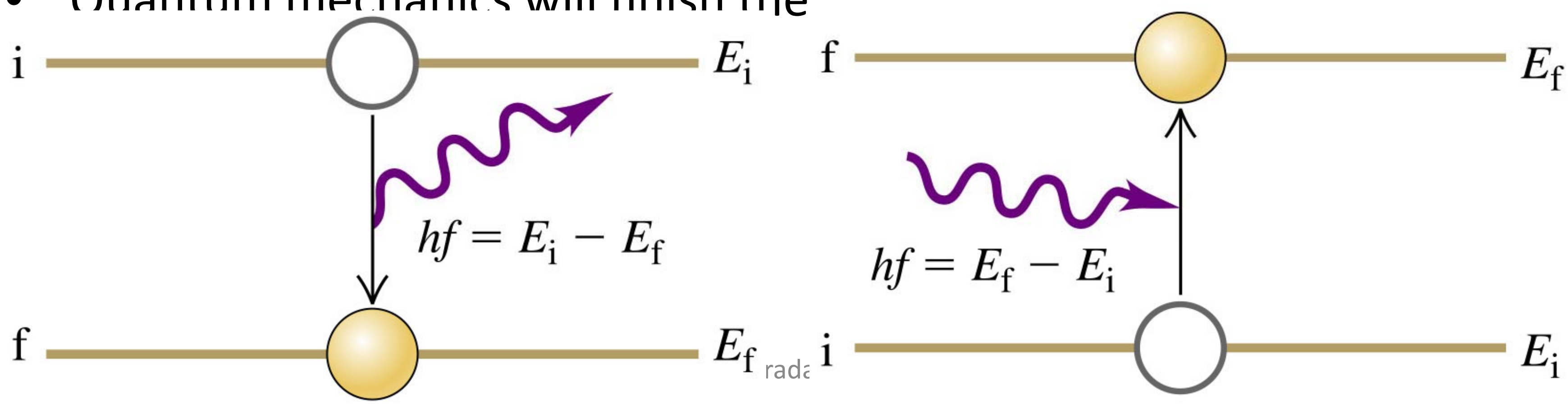
We will come back to study the theoretical model known as th Bohr model that attempts to explain these spectral lines.



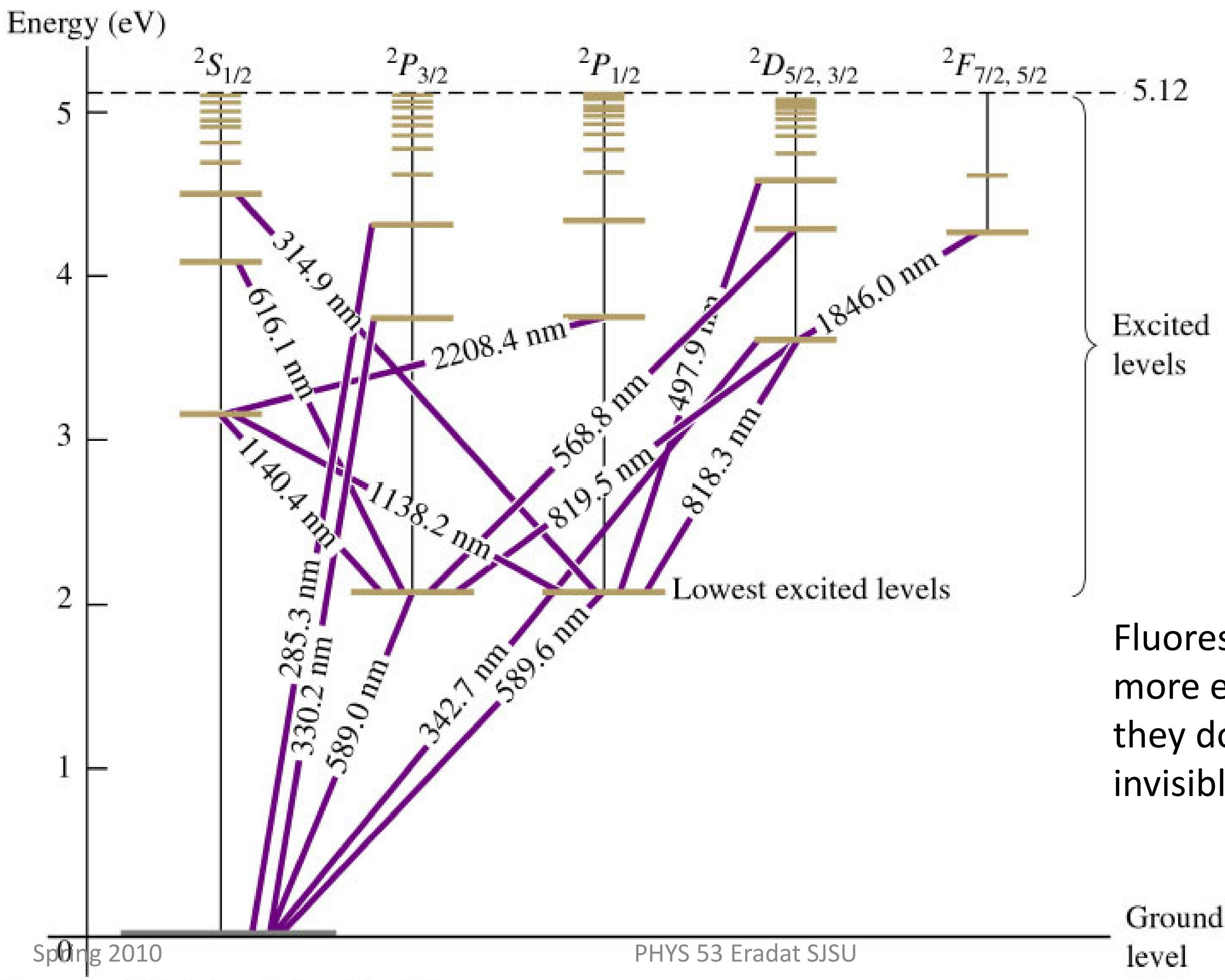
(b)

Energy levels & Bohr Model of atom

- Ground state (level): Every atom has a lowest energy level that includes the lowest internal energy possible for it.
- Excited states (levels): All the levels with higher energy content are excites states.
- Excited states are not stable and atoms in these states want to transition to the ground state by emitting one or more photons.
- Atoms also can go from a lower state to a higher state by absorbing a photon.
- This is the Bohr model and successful on explanation of the origin of the atomic spectra but failed on explanation of the details of spectra for each atom.
- Quantum mechanics will finish the



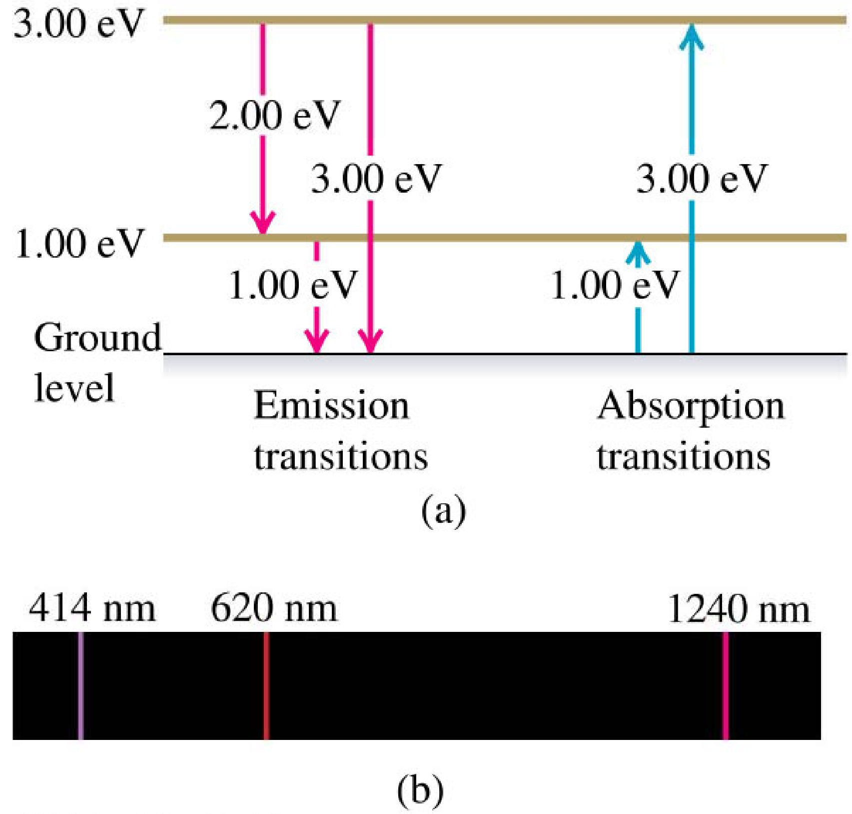
Energy levels of a Sodium atom
Emission & Absorption spectra, fluorescence



Fluorescent lamps are more efficient because they do not produce invisible light.

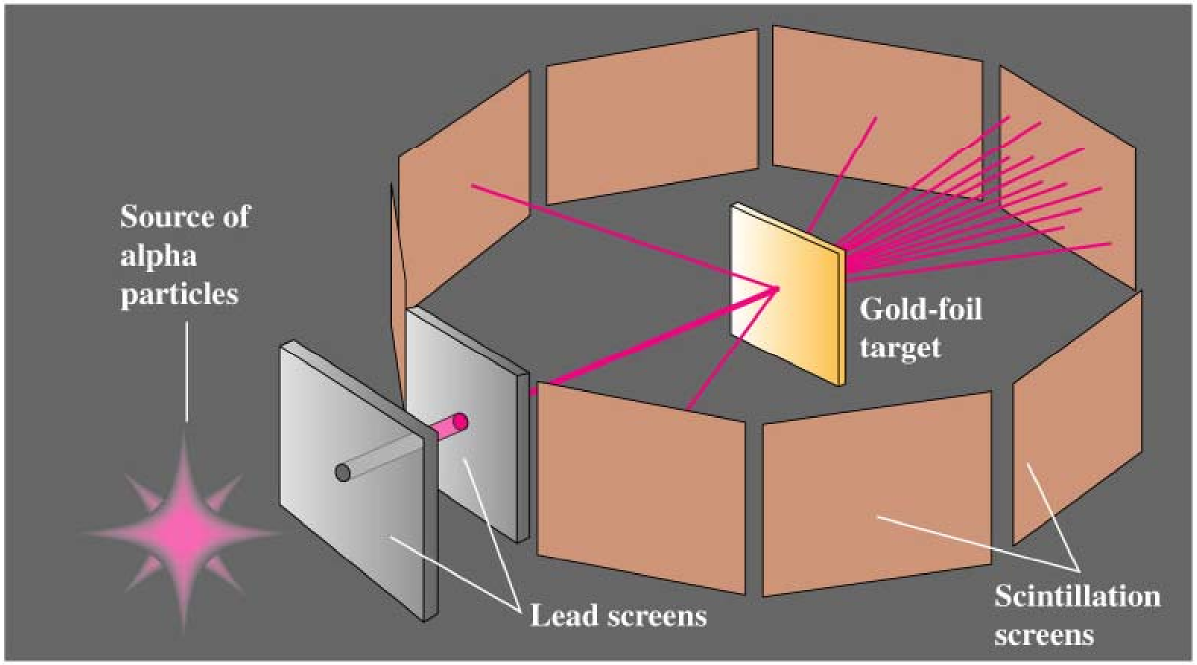
Emission & Absorption spectra

- An atom has three levels, ground level, and two levels 1.0eV and 2.0eV above it. Find the frequencies and wavelengths of the photons this atom can absorb or emit when excited?

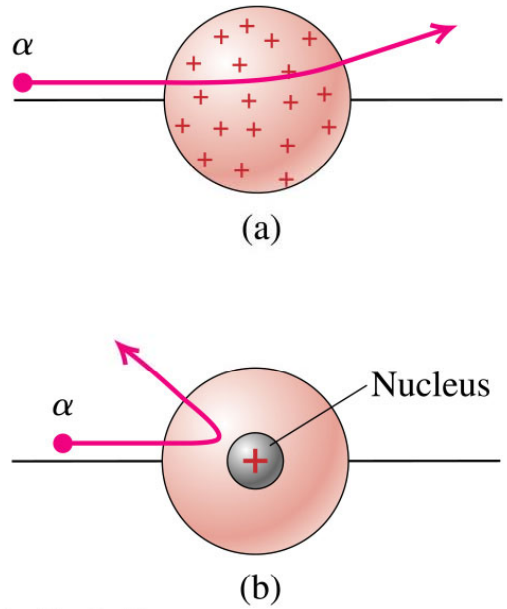


The nuclear atom

- 1897 Thomson discovered the charge-to mass ratio or e/m
- 1909 Millikan measured the electron charge –e
- Experiments suggested that mass of the atom is mostly associated with its + charge.
- 1910-1911 Rutherford designed an experiment to explain the structure of the atom



Thompson Model and Rutherford scattering experiment

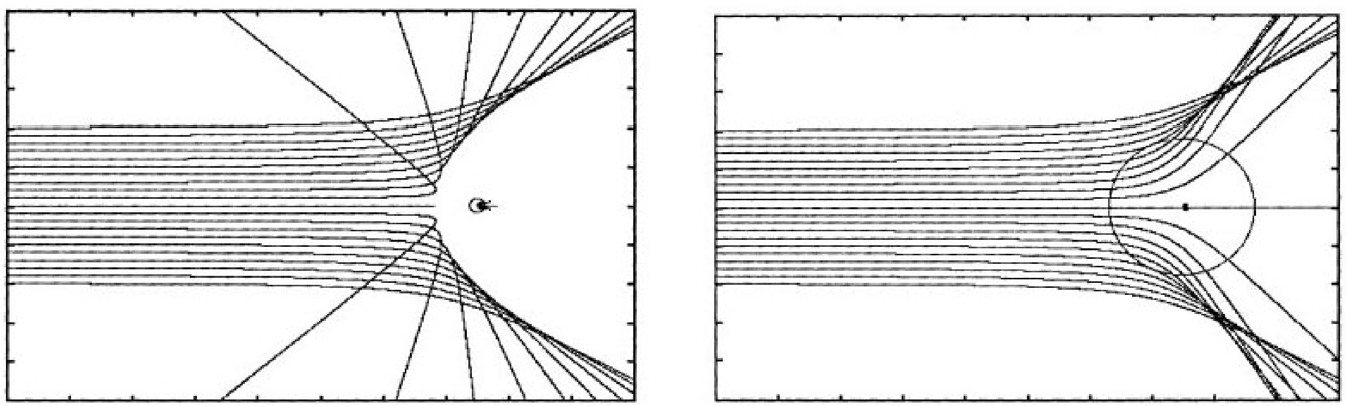


Computer simulation of the Rutherford experiment

5.0 MeV alpha particles

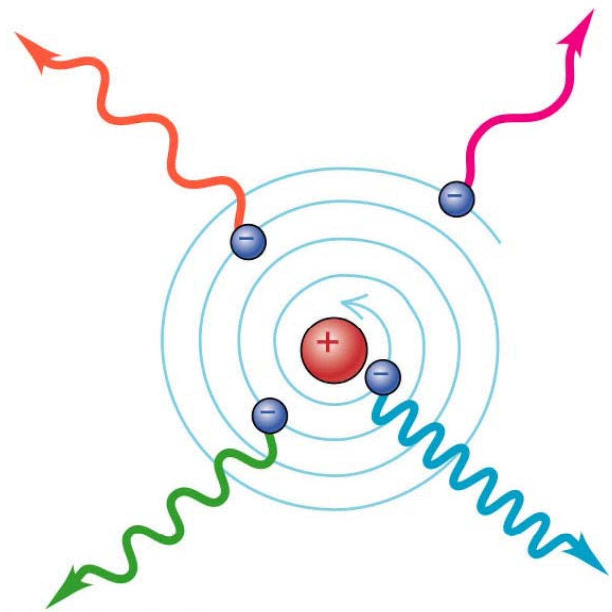
a) A model with estimated radius of nucleus= 7.0E-15 m

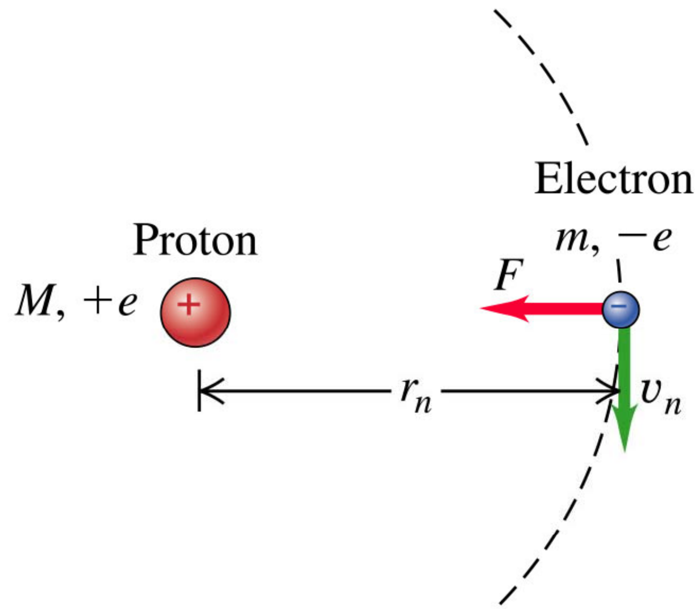
b) A model with larger radius and does not match the data

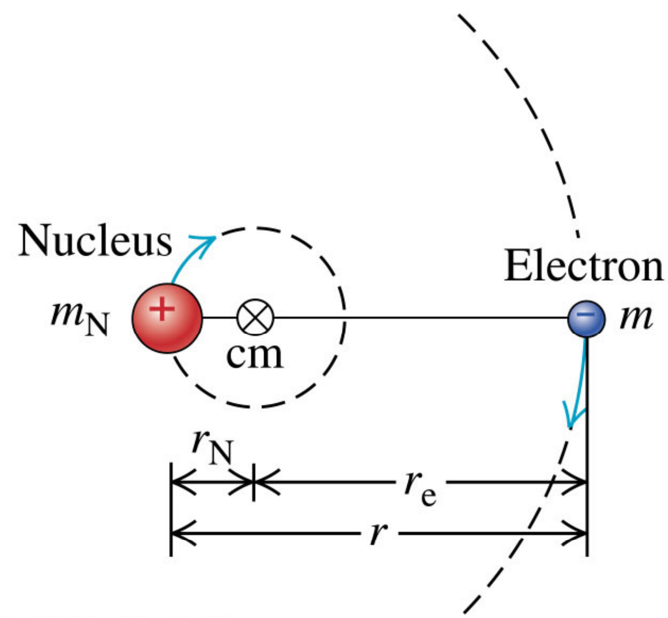


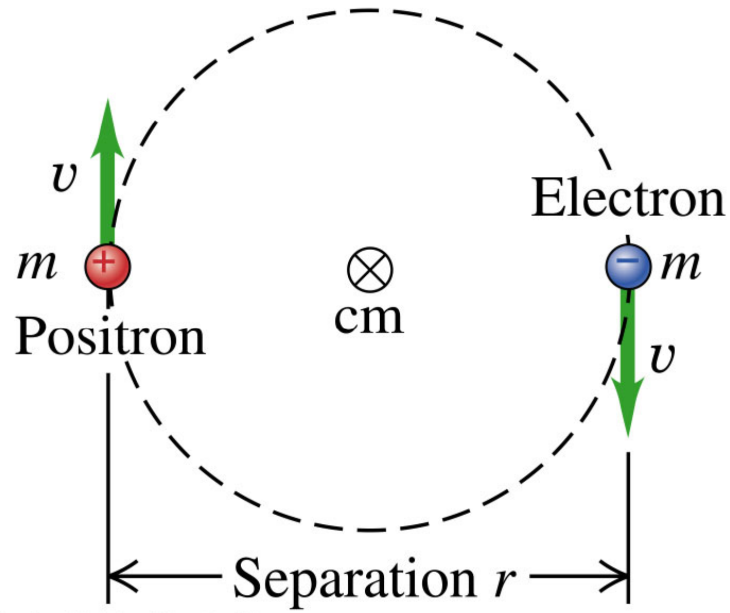
(a) (b)

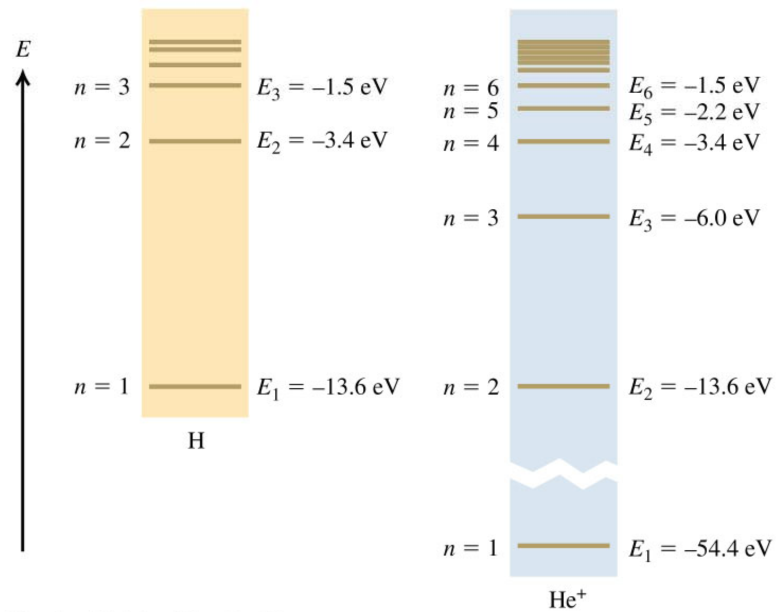
The Bohr Model

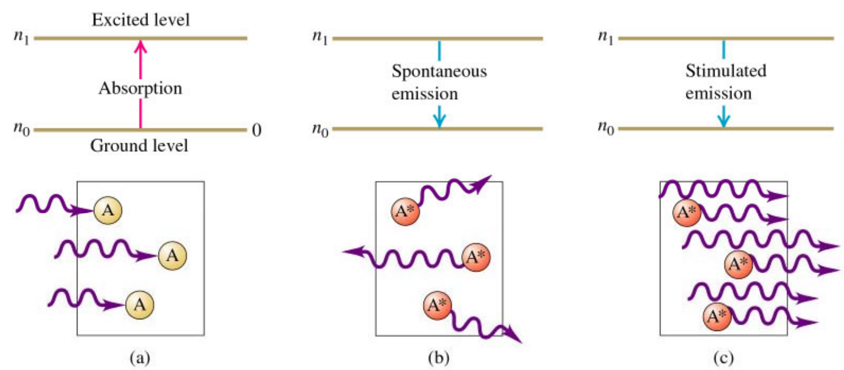


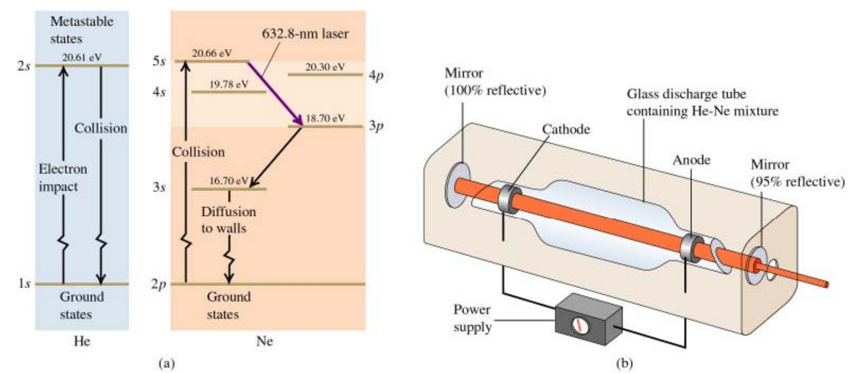

Electron
$m, -e$
Proton
$M, +e$
F
r_n
v_n

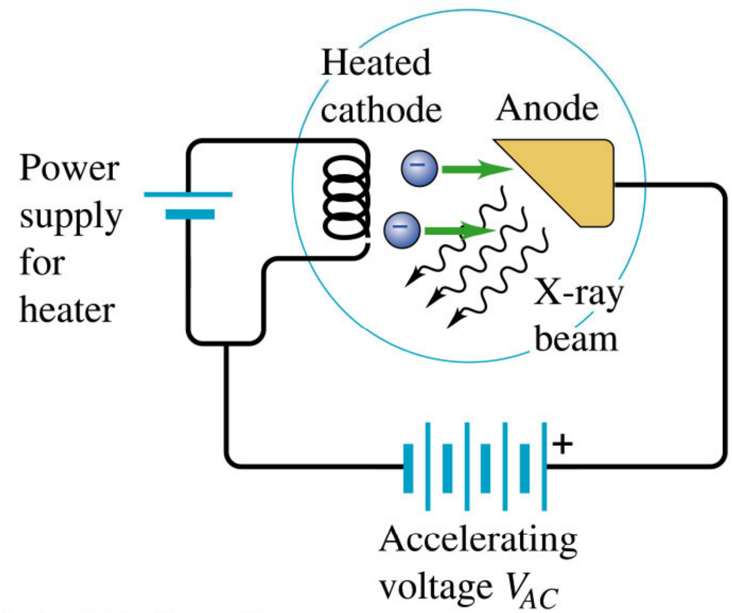

Nucleus
m_N
cm
Electron
m
r_N
r_e
r

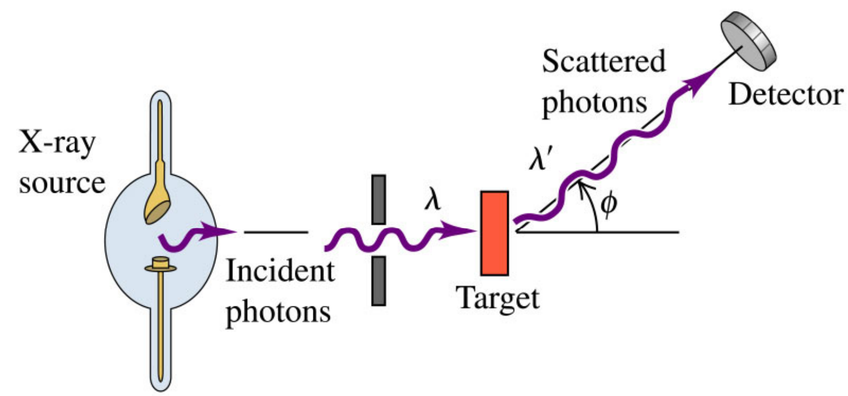

v
Electron
m
m
Positron
cm
v
Separation r

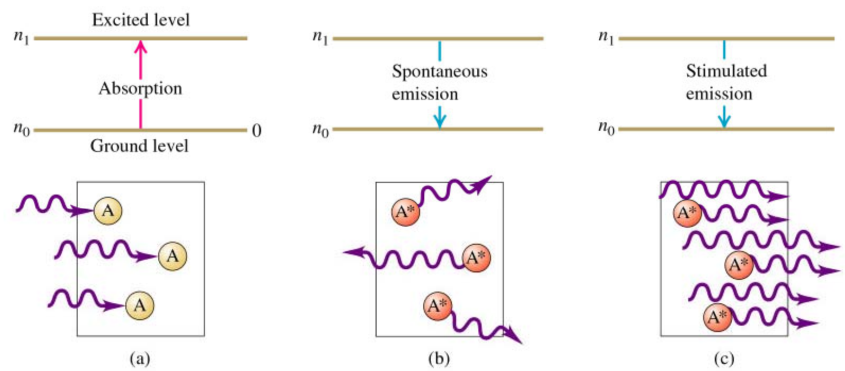

E
n = 3
E3 = –1.5 eV
n = 2
E2 = –3.4 eV
n = 1
E1 = –13.6 eV
H
n = 6
E6 = –1.5 eV
n = 5
E5 = –2.2 eV
n = 4
E4 = –3.4 eV
n = 3
E3 = –6.0 eV
n = 2
E2 = –13.6 eV
n = 1
E1 = –54.4 eV
He+

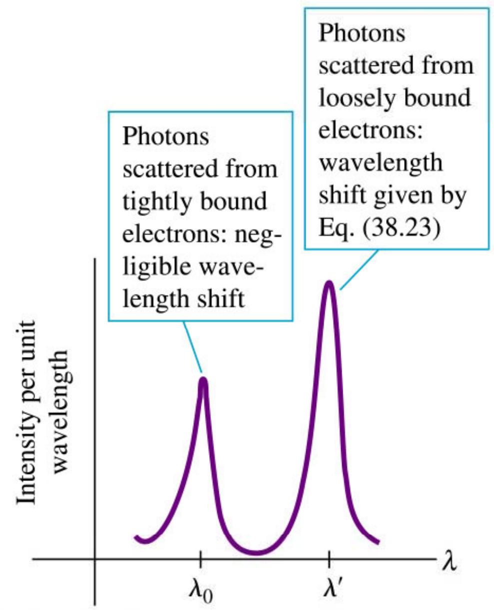

Excited level
n_1
Absorption
n_0
0
Ground level
A
(a)
n_1
Spontaneous emission
n_0
A*
(b)
n_1
Stimulated emission
n_0
A*
(c)

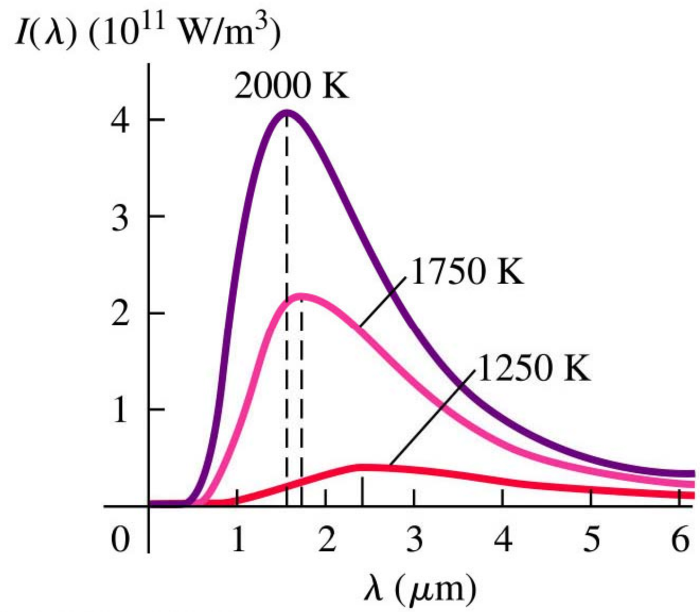

Metastable states
20.61 eV
2s
1s
Collision
Electron impact
Ground states
He
632.8-nm laser
20.66 eV
5s
19.78 eV
4s
20.30 eV
4p
18.70 eV
3p
Collision
16.70 eV
3s
Diffusion to walls
2p
Ground states
Ne
(a)
Mirror (100% reflective)
Glass discharge tube containing He-Ne mixture
Cathode
Anode
Mirror (95% reflective)
Power supply
(b)

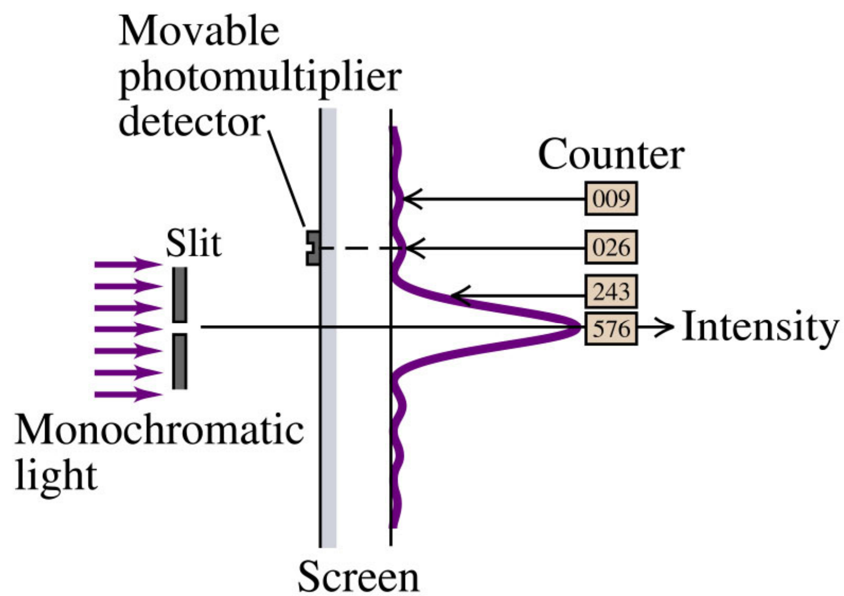

Heated
cathode
Anode
Power
supply
for
heater
X-ray
beam
+
Accelerating
voltage V_{AC}

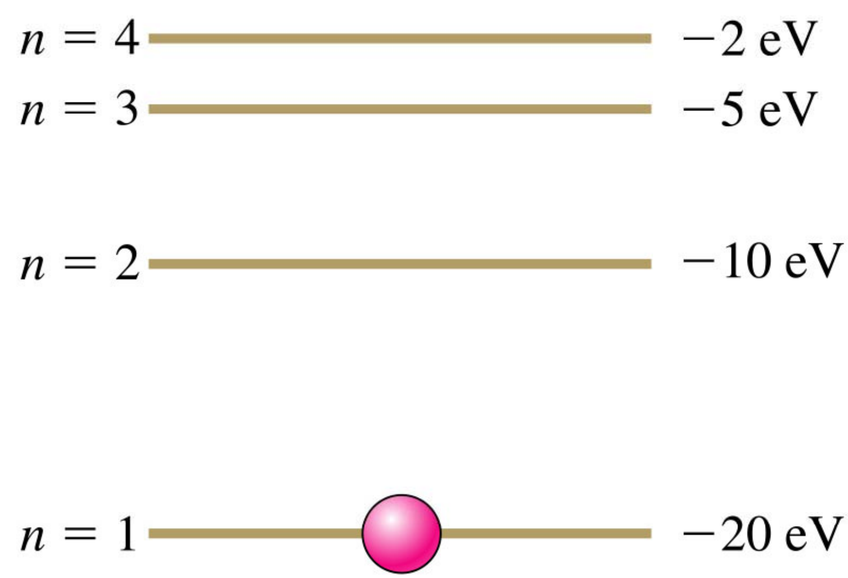

X-ray
source
Incident
photons
λ
Target
λ'
ϕ
Scattered
photons
Detector


Excited level
n_1
Absorption
n_0
0
Ground level
A
A
A
(a)
n_1
Spontaneous emission
n_0
A*
A*
A*
(b)
n_1
Stimulated emission
n_0
A*
A*
A*
(c)


Photons scattered from tightly bound electrons: negligible wavelength shift
Photons scattered from loosely bound electrons: wavelength shift given by Eq. (38.23)
Intensity per unit wavelength
λ
λ₀
λ′


$I(\lambda)$ (10^{11} W/m^3)
2000 K
1750 K
1250 K
4
3
2
1
0
1
2
3
4
5
6
λ (μm)


Movable
photomultiplier
detector
Counter
009
Slit
026
243
576
Intensity
Monochromatic
light
Screen



n = 4
−2 eV
n = 3
−5 eV
n = 2
−10 eV
n = 1
−20 eV