CHEM 115
Waves, Radiation, and Spectroscopy

Lecture 16
Prof. Sevian

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Announcements (1)

- Challenge problem
  - Due today at 2:00 promptly (late papers will not be accepted) - place in the box at the front of the room
  - I will grade them and return to you on Thursday in class
  - We will go over the solution as part of the review for Exam 2, which we will do on Thursday
  - Material covered in class today will not be on Exam 2, however, what we are doing in today's lecture forms the foundation for understanding the material for the rest of the semester

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Announcements (2)

- Please do the survey that you will receive information about tomorrow via email
  - I sent you an email about this
  - Email will be from umbinfo@umb.edu
  - It will arrive in your UMB student email and will contain a link to an online survey
  - Subject line will be “Professional Science Master’s Degree Survey and Raffle”
  - Purpose of the survey is to help the UMass system learn how to best set up a professional master’s in science degree program to be what students want
  - There is a raffle and you could win a gift certificate to the UMass bookstore
  - Online survey takes 10-15 minutes to complete
  - Deadline for taking survey is Monday, April 13

Agenda

- Intro to waves and radiation
  - Waves
    - Features of waves (speed, wavelength, frequency, energy)
    - Mathematical relations between features
  - Wave-particle duality of light energy
    - Phenomena (properties) that can be described by one but not the other
  - If light can be described by wave-particle duality, why not also electrons?
- Specific matter-energy interactions
  - Photoelectric effect (light energy in, generates electrons)
  - Spectroscopy (electrons absorb energy, then give off light energy as they relax back to lower energy levels)

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Map of Chapter 6

- Waves
  - Light (energy)
  - Matter
  - Are matter and energy really the same thing (on some scale)?
- Wave-matter duality
  - Black body radiation and photoelectric effect
  - Quantization of energy
- The quantum mechanical model
  - Spectroscopy: a phenomenon in need of explanation
  - How to use the quantum mechanical model
  - What the model explains/predicts
  - Where the model breaks down

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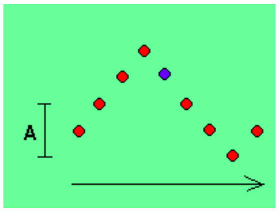
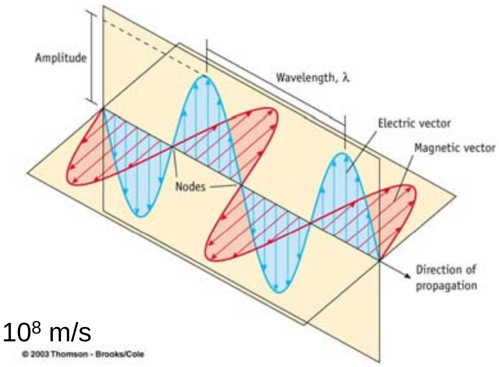
Describing Waves



- For waves requiring a medium in which to travel, wave is a manifestation of kinetic energy of particles of medium
- Particles in medium move up and down with a particular frequency (ups & downs per second)
- Animation at right: although the wave appears to be moving to the right, if you fix your eye on the motion at one location (look at the blue particle) the particle at that point is “bobbing” up and down
- Other important parameters to describe waves
  - Wavelength (λ): length (distance in meters) of one cycle
  - Amplitude (**A**): maximum distance a particle gets from its undisturbed position
  - Frequency (ν or f): number of cycles (“bobs” up & down) per second
  - Speed: given by [**frequency** (cycles/s)] x [**wavelength** (meters/cycle)]

see http://www.ewart.org.uk/science/Waves/wav1.htm



Light and other electromagnetic waves

Speed of light in a vacuum

$c = 3.00 \times 10^8$ m/s

Therefore $c = \nu \lambda$

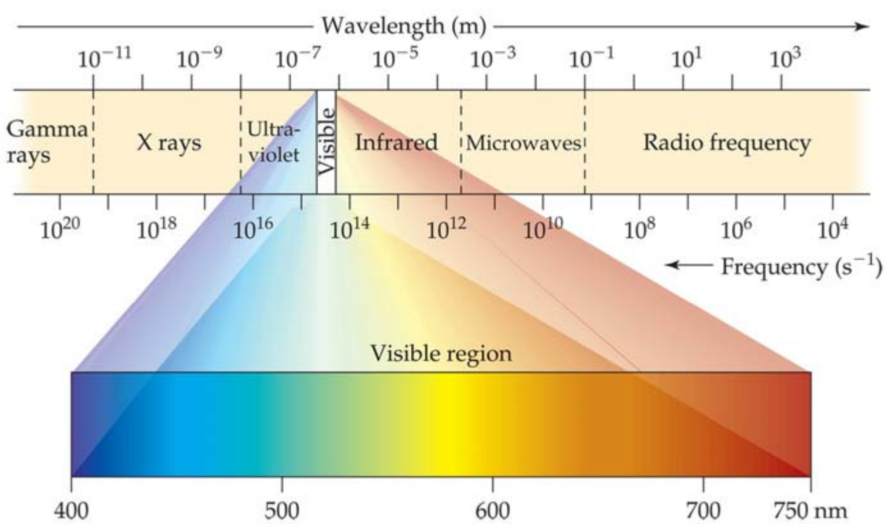
frequency (Hz or cycles/s)

wavelength (m or m/cycle)

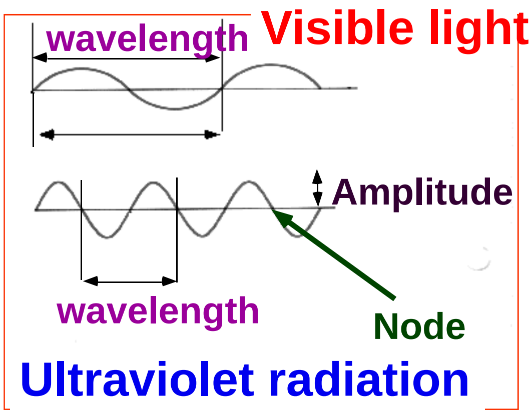
How to create an electromagnetic wave:

- An oscillating electric field generates an oscillating magnetic field
- Vice versa

Electromagnetic spectrum divided up based on frequency



How light waves differ from each other



Summary of language chemists use:
Wavelength: long/short
Frequency: low/high

Compare visible and UV light:

Both are light, so they have the same velocity (speed of light, c = 3.0 x 10^8 m/s)

Wavelength (Greater than, less than, or equal?)

λ_{visible} ○ λ_{UV}

Frequency

ν_{visible} ○ ν_{UV}

Calculation of Light Properties

Red light has λ = 690 nm. What is its frequency?

Convert wavelength to standard SI units:

$$690\ nm \times \frac{10^{-9}\ m}{1\ nm} = 6.9 \times 10^{-7}\ m$$

Calculate frequency:

$$\boxed{c = \lambda\nu} \quad \therefore \quad \nu = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\ m/s}{6.9 \times 10^{-7}\ m} = 4.35 \times 10^{14}\ s^{-1} \text{ or } Hz$$

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Black Body Radiation

- Objects below ~700 K produce very little radiation in the visible range
- As the temperature increases, both the intensity and the frequency (ν) of the radiation increases
- Classical physics predicts that the energy of light depends on its intensity

- This leads to the prediction that as the frequency increases, so does the intensity
- *Ultraviolet catastrophe*

The red glow of lava is due to its temperature of 1000 to 1200ºC

Black Body Radiation

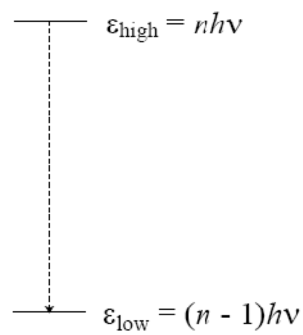
Have you seen it before?

- Why does it glow red/orange when the burner is set to "high" but there is no glow when the burner is on "low"?

- What would happen if you could turn up the burner to "superhigh"?

Planck's Genius

- An object contains oscillators with various individual frequencies, ν
- Each oscillator has energies restricted to quantized values,
  $\varepsilon_n = nh\nu$
  (n = 1, 2, 3, 4, …)
- Oscillators emit energy in the form of light when they transition from ε_{high} to ε_{low}



Therefore, light energy is proportional to ν not intensity

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Wave-Particle Duality of Light

- Light can be described by frequency, wavelength of various colors of visible light, and of non-visible light (*e.g.*, microwaves, IR)
- Blackbody radiation from hot objects and "ultraviolet catastrophe" solved by Planck's equation which explains that a blackbody is made of a bunch of oscillating atoms, and the energies of each oscillating atom are *quantized*
  - Planck: Energy of an oscillating atom depends on frequency of the oscillation
    $E = nh\nu$ (with n = 1, 2, 3, …)
  - Einstein: electromagnetic waves have particle nature

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Other Properties of Light

Property	***Wave behavior***	***Particle behavior***
Reflection	∿	●
Refraction	∿	●
Interference	∿	×
Diffraction	∿	×
Polarization	∿	×
Photoelectric effect	×	●

Modified from http://www.opticshare.com/resource/14.asp

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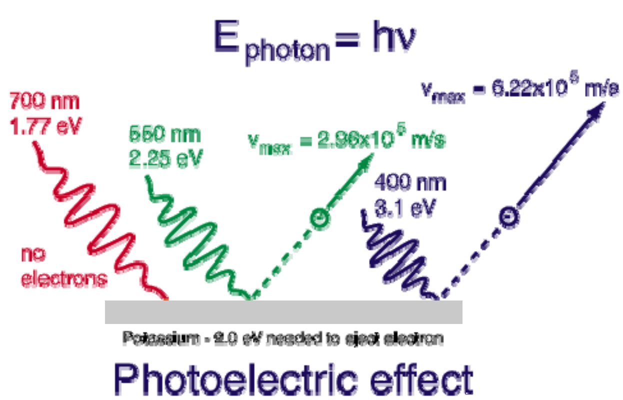
Photoelectric Effect

Property of light that can be explained only by particle behavior

- Shining light on a metal can free electrons from the surface
- Easy for UV light to do this, difficult for red light
- Kinetic energy (also velocity) of freed electrons depends on frequency of light
- Increasing the intensity of the light frees more electrons but doesn't change the energies of electrons freed



From http://www.opticshare.com/resource/14.asp

Photoelectric effect

Switch over to simulation

Where I got this from:

http://phet.colorado.edu/new/simulations/sims.php?sim=Photoelectric_Effect

More generally, see

http://phet.colorado.edu/new/index.php

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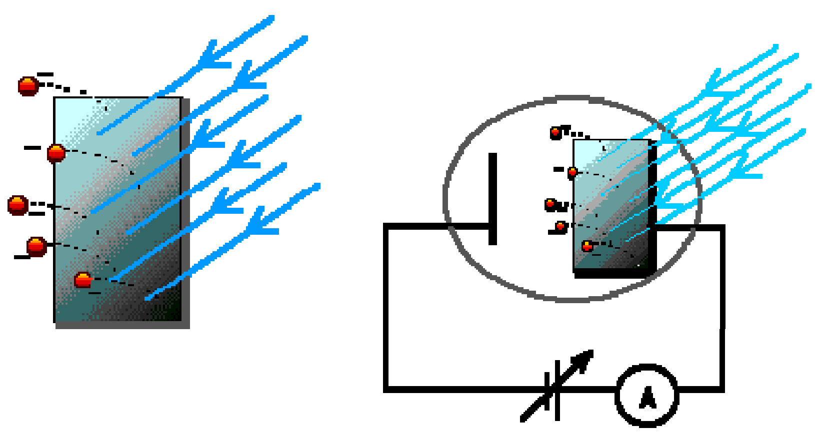
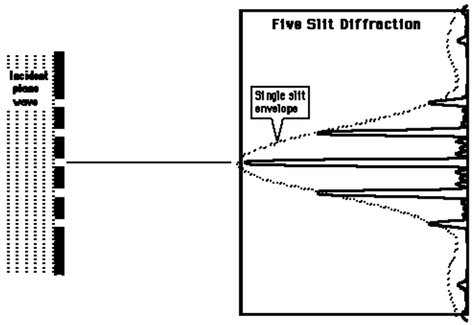
Photoelectric Effect is Useful

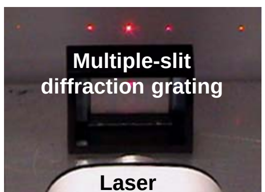


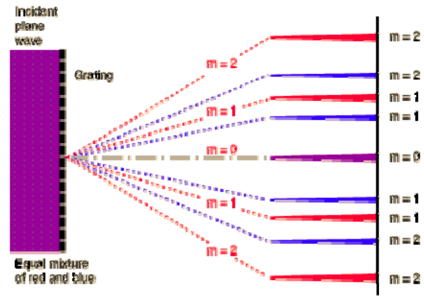
From www.ux1.eiu.edu/~cfadd/ 1160/Ch28QM/Photo.html

Diffraction

Property of light that can be explained only by wave behavior







From http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html

Key points so far today

- Waves can be described by three interrelated measurements: wavelength, speed and frequency
  - These are related by $c = \lambda \cdot \nu$
  - Remember to pay attention to units
    - Wavelength in nm vs. m
    - Frequency has units s^{-1} or Hz
- Energy of a wave is proportional to frequency
  - These are related by $E = h \cdot \nu$
- Some properties of light are explained by wave behavior (e.g., diffraction)
- Other properties of light are explained by particle behavior (e.g., photoelectric effect)

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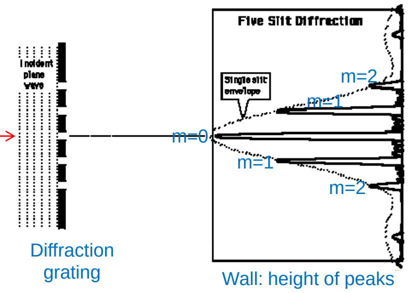
Building an understanding of diffraction

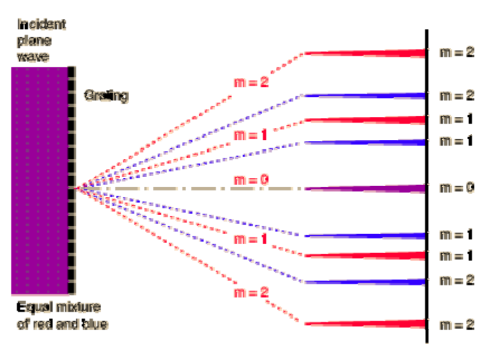


Wall: height of peaks is showing intensity (brightness) of light

- A laser beam passes through a diffraction grating and you see light on the wall after it.
- If light is particles, and if a laser beam is a stream of light particles all going in the same direction, what would you expect to see on the wall?
- Particle model doesn't work to describe diffraction, but wave model does work
- Peaks seen on the wall:
  - m = 0 is the one directly across from the incident laser beam (this one is the brightest)
  - m = 1 peaks are the next ones out, on both sides (these are less intense than the m=0 center peak)
  - m = 2 peaks are the ones after that, on both sides (these are less intense than the m=1 peaks)
  - and so on…
- Distance of peaks from center depends on the wavelength of laser light
  - Shorter wavelengths (toward violet), closer peaks
  - Longer wavelengths (toward red), peaks farther apart

Using a diffraction grating

- You can use your diffraction grating to separate out the different (narrow bands of) wavelengths of light coming from a source that is emitting more than one color (wavelength) of light



Does Wave-Particle Duality Apply to Electrons?

Photoelectric effect:

Photons (particles of light) cause electrons to be ejected from atoms

Can converse work?

Can electrons moving cause photons to be ejected from atoms?

Light behaves as waves sometimes and particles sometimes

So…

What about electrons, which are very small particles?

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Using a diffraction grating to observe emission spectra

- Take a diffraction grating
- Look through it at white light. What do you see? Why?
- If you were looking at monochromatic light (such as a laser) through it, what would you see? Why? (Note: we're not going to send laser light through it toward your eye)
- Look at the emission spectrum of hydrogen. What do you see?
- Look at the emission spectrum of another element. What do you see?
- Why are they different? What is going on?

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A simulation of the hydrogen emission spectrum

Physics Education Technology (PhET) at CU Boulder
http://phet.colorado.edu/new/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom

You may want to play with this on your own time also.
Here are some ideas to consider:

- Which model most closely matches experiment?
- Which model does the Rydberg equation come from?
- How are other elements different from hydrogen?

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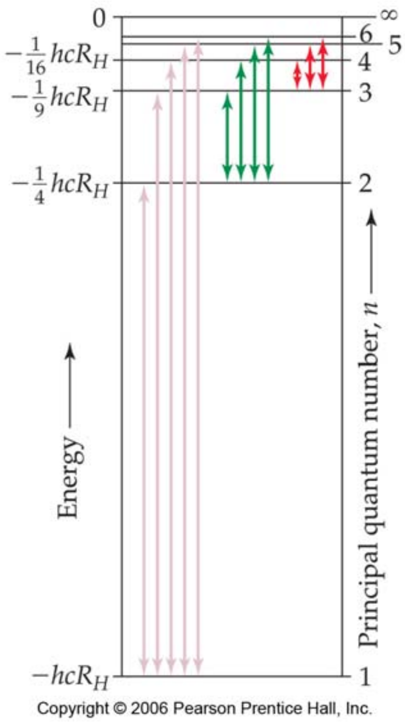
Models to describe the hydrogen emission spectrum

(write down some notes here about each model)

Emission Spectrum of Hydrogen



Note that this picture explains the photoelectric effect phenomenon

Bohr Theory

Bohr first thought to mathematically model electrons as in orbit around nucleus, and when "quantization postulate" applied, Bohr's model correctly predicts hydrogen spectrum that is experimentally seen

Rydberg equation:

$$\Delta E = -hcR_H\left(\frac{1}{n_{final}^2} - \frac{1}{n_{initial}^2}\right)$$

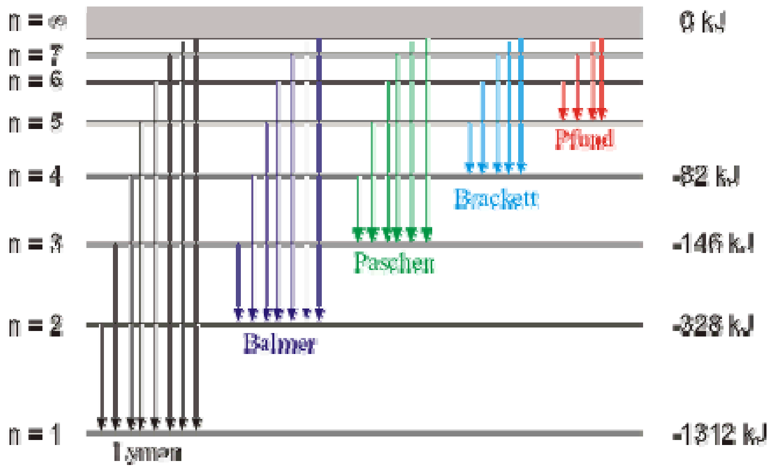
where $hcR_H = 2.18\times10^{-18}\ J$

See equation 6.5, p. 226

Emission Spectrum of Hydrogen

$$\Delta E = -hcR_H\left(\frac{1}{n_{final}^2} - \frac{1}{n_{initial}^2}\right)$$

where $hcR_H = 1312\ {kJ}/{mol}$



See http://www.ktf-split.hr/glossary/image/emission_spectrum_of_hydrogen.gif