Unit II - Lecture 6

Chemistry

The Molecular Nature of Matter and Change

Fifth Edition

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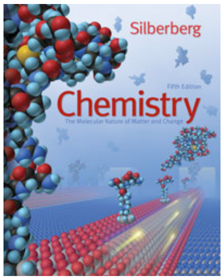


Quantum Theory and Atomic Structure

7.1 The Nature of Light

7.2 Atomic Spectra

7.3 The Wave-Particle Duality of Matter and Energy

The Wave Nature of Light

Figure 7.1

Frequency and Wavelength

$c = \lambda\nu$

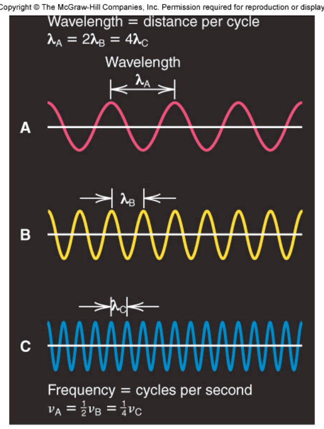


Figure 7.2 **Amplitude (intensity) of a wave.**

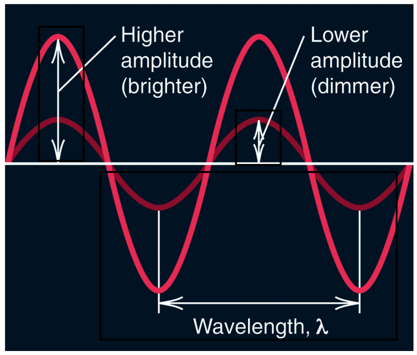
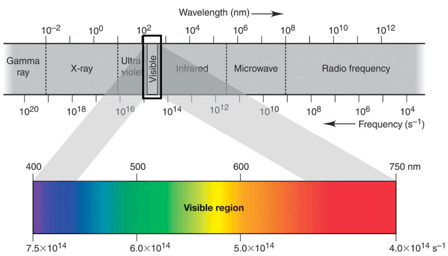


Figure 7.3 **Regions of the electromagnetic spectrum.**



Sample Problem 7.1 **Interconverting Wavelength and Frequency**

PROBLEM: A dental hygienist uses x-rays (λ= 1.00 Å) to take a series of dental radiographs while the patient listens to a radio station (λ = 325 cm) and looks out the window at the blue sky (λ= 473 nm). What is the frequency (in s^{-1}) of the electromagnetic radiation from each source? (Assume that the radiation travels at the speed of light, 3.00×10^8 m/s.)

PLAN: Use $c = \lambda\nu$

wavelength in units given

$1\ Å = 10^{-10}$ m
$1\ cm = 10^{-2}$ m
$1\ nm = 10^{-9}$ m

wavelength in m

$\nu = c/\lambda$

frequency (s^{-1} or Hz)

SOLUTION:

$1.00\ Å \times \frac{10^{-10}\ m}{1\ Å} = 1.00\times10^{-10}\ m$

$\nu = \frac{3\times10^8\ m/s}{1.00\times10^{-10}\ m} = 3\times10^{18}\ s^{-1}$

$325\ cm \times \frac{10^{-2}\ m}{1\ cm} = 325\times10^{-2}\ m$

$\nu = \frac{3\times10^8\ m/s}{325\times10^{-2}\ m} = 9.23\times10^{7}\ s^{-1}$

$473\ nm \times \frac{10^{-9}\ m}{1\ nm} = 473\times10^{-9}\ m$

$\nu = \frac{3\times10^8\ m/s}{473\times10^{-9}\ m} = 6.34\times10^{14}\ s^{-1}$

Figure 7.4

Different behaviors of waves and particles.

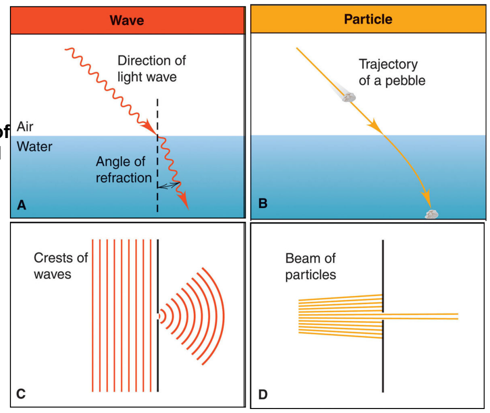


Figure 7.5 **The diffraction pattern caused by light passing through two adjacent slits.**

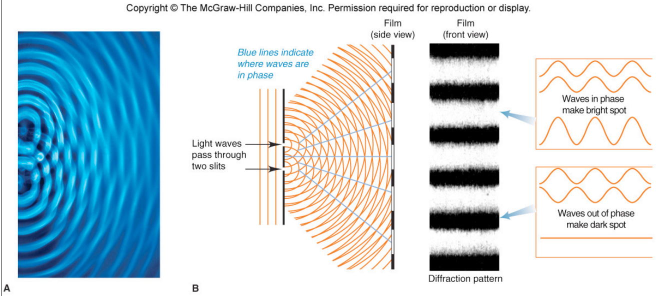
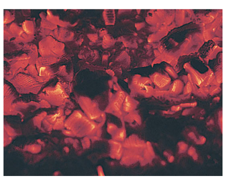


Figure 7.6 **Blackbody radiation**



Smoldering coal

$$E = nh\nu$$

$$\Delta E = \Delta n h\nu$$

$$\Delta E = h\nu$$

when $n = 1$

Electric heating element

Lightbulb filament

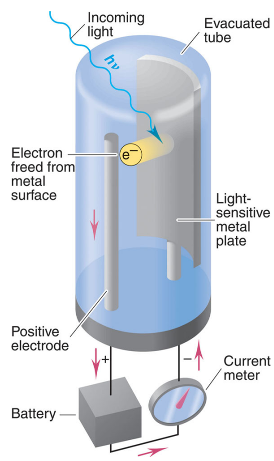


Figure 7.7

Demonstration of the photoelectric effect.

Sample Problem 7.2 **Calculating the Energy of Radiation from Its Wavelength**

PROBLEM: A cook uses a microwave oven to heat a meal. The wavelength of the radiation is 1.20 cm. What is the energy of one photon of this microwave radiation?

PLAN: After converting cm to m, we can use the energy equation, $E = h\nu$ combined with $\nu = c/\lambda$ to find the energy.

SOLUTION: $E = hc/\lambda$

$$E = \frac{6.626\text{x}10^{-34}\ \text{J*s} \times 3\text{x}10^{8}\ \text{m/s}}{1.20\ \text{cm}\ \frac{10^{-2}\ \text{m}}{1\ \text{cm}}} = 1.66\text{x}10^{-23}\ \text{J}$$

Figure 7.8

The line spectra of several elements.

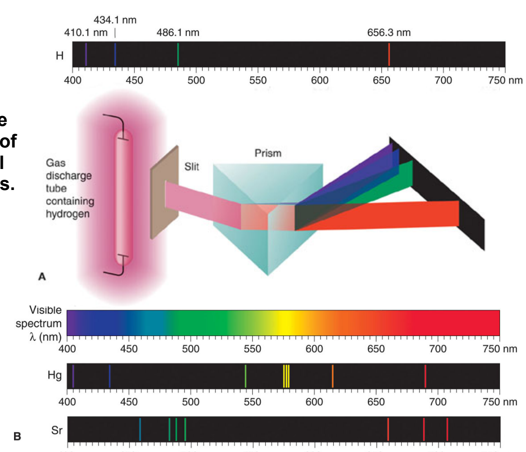
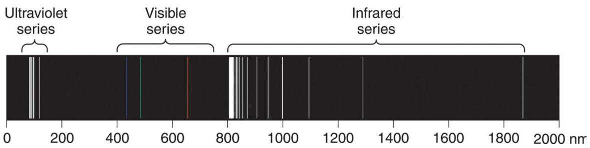


Figure 7.9 **Three series of spectral lines of atomic hydrogen.**



Rydberg equation

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

R is the Rydberg constant = 1.096776x10^{7} m^{-1}

for the visible series, n_1 = 2 and n_2 = 3, 4, 5, ...

Figure 7.10

Quantum staircase.

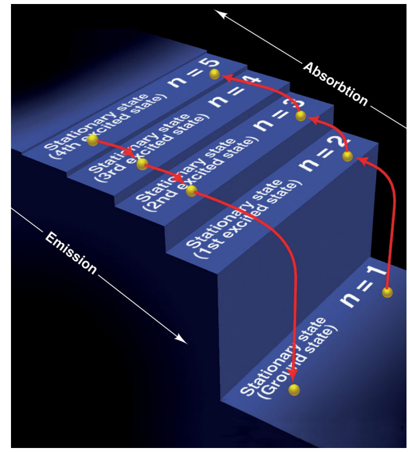


Figure 7.11 **The Bohr explanation of three series of spectral lines.**

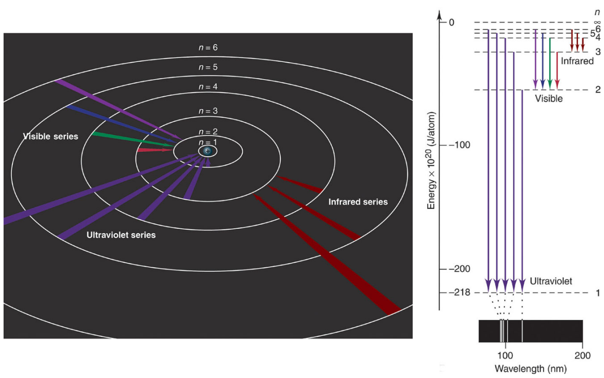
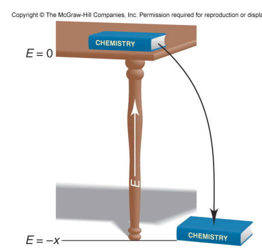


Figure 7.12 **A tabletop analogy for the H atom's energy.**



$$\Delta E = E_{final} - E_{initial} = -2.18 \times 10^{-18}\ J\left(\frac{1}{n^2_{final}} - \frac{1}{n^2_{initial}}\right)$$

Sample Problem 7.3 **Determining ΔE and λ of an Electron Transition**

PROBLEM: A hydrogen atom absorbs a photon of visible light (see Figure 7.11) and its electron enters the n = 4 energy level. Calculate (a) the change in energy of the atom and (b) the wavelength (in nm) of the photon.

PLAN: The H atom absorbs energy, so $E_{final} > E_{initial}$. Visible light is absorbed when $n_{initial}$ = 2. Calculate ΔE using equation 7.4. (b) Use equations 7.2 and 7.1 to calculate wavelength and convert to nm.

SOLUTION: **(a)**

$$\Delta E = -2.18 \times 10^{-18}\ J\left(\frac{1}{n^2_{final}} - \frac{1}{n^2_{initial}}\right) = -2.18 \times 10^{-18}\ J\left(\frac{1}{4^2} - \frac{1}{2^2}\right)$$

$$= -2.18 \times 10^{-18}\ J\left(\frac{1}{16} - \frac{1}{4}\right) = 4.09 \times 10^{-19}\ J$$

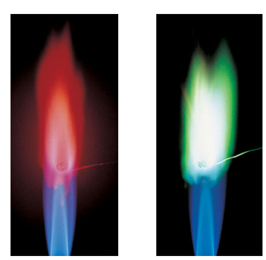
(b)

$$\lambda = hc/\Delta E = \frac{6.626 \times 10^{-34}\ J{*}s \times 3 \times 10^{8}\ m/s}{4.09 \times 10^{-19}\ J} = 4.86 \times 10^{-7}\ m \times \frac{1\ nm}{10^{-9}\ m} = 486\ nm$$

Figure B7.1 A

Flame tests.

strontium $_{38}$Sr



copper $_{29}$Cu

Figure B7.2 **Emission and absorption spectra of sodium atoms.**

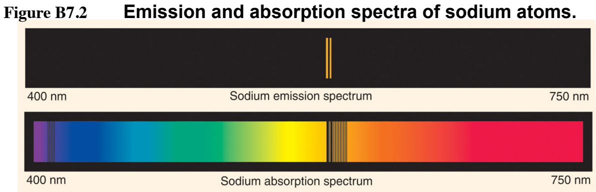


Figure B7.1 B

Figure B7.3 **The main components of a typical spectrometer.**

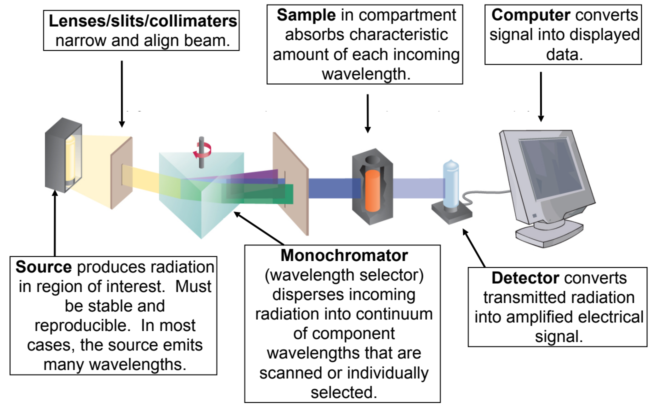


Figure B7.4 **Measuring chlorophyll *a* concentration in leaf extract.**

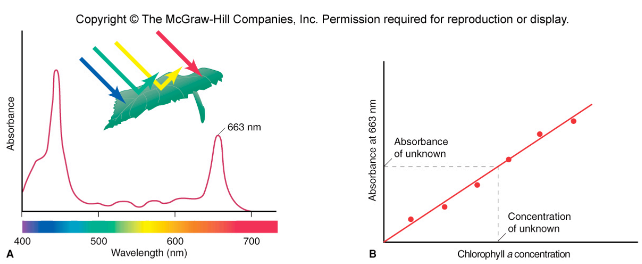


Figure 7.13

Wave motion in restricted systems.

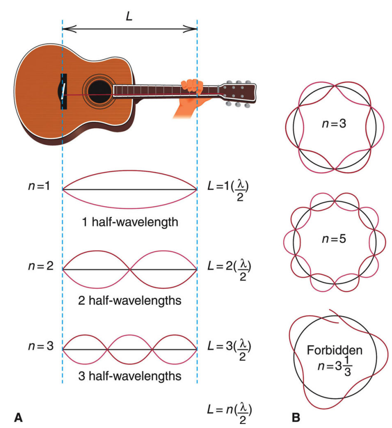


Table 7.1 The de Broglie Wavelengths of Several Objects

Substance	Mass (g)	Speed (m/s)	λ (m)
slow electron	9×10^{-28}	1.0	7×10^{-4}
fast electron	9×10^{-28}	5.9×10^{6}	1×10^{-10}
alpha particle	6.6×10^{-24}	1.5×10^{7}	7×10^{-15}
one-gram mass	1.0	0.01	7×10^{-29}
baseball	142	25.0	2×10^{-34}
Earth	6.0×10^{27}	3.0×10^{4}	4×10^{-63}

$$\lambda = h/mu$$

Sample Problem 7.4 Calculating the de Broglie Wavelength of an Electron

PROBLEM: Find the deBroglie wavelength of an electron with a speed of 1.00×10^{6} m/s (electron mass = 9.11×10^{-31} kg; $h = 6.626\times10^{-34}$ kg*m²/s).

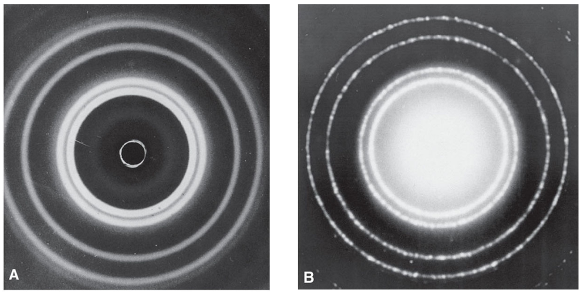
PLAN: Knowing the mass and the speed of the electron allows to use the equation $\lambda = h/mu$ to find the wavelength.

SOLUTION:

$$\lambda = \frac{6.626\times10^{-34}\ \text{kg*m}^2/\text{s}}{9.11\times10^{-31}\ \text{kg} \times 1.00\times10^{6}\ \text{m/s}} = 7.27\times10^{-10}\ \text{m}$$

Figure 7.14

Comparing the diffraction patterns of x-rays and electrons.



x-ray diffraction of aluminum foil | electron diffraction of aluminum foil

Figure 7.15

Summary of the major observations and theories leading from classical theory to quantum theory.

CLASSICAL THEORY

Matter	**Energy**
particulate, massive	continuous, wavelike

Since matter is discontinuous and particulate perhaps energy is discontinuous and particulate.

Observation		*Theory*
blackbody radiation	→	Planck: Energy is quantized; only certain values allowed
photoelectric effect	→	Einstein: Light has particulate behavior (photons)
atomic line spectra	→	Bohr: Energy of atoms is quantized; photon emitted when electron changes orbit.

Figure 7.15 continued

Since energy is wavelike perhaps matter is wavelike

Observation		*Theory*
Davisson/Germer: electron diffraction by metal crystal	←	deBroglie: All matter travels in waves; energy of atom is quantized due to wave motion of electrons

Since matter has mass perhaps energy has mass

Observation		*Theory*
Compton: photon wavelength increases (momentum decreases) after colliding with electron	←	Einstein/deBroglie: Mass and energy are equivalent; particles have wavelength and photons have momentum.

QUANTUM THEORY

Energy same as Matter
particulate, massive, wavelike

The Heisenberg Uncertainty Principle

$$\Delta x \ * \ m\,\Delta u \geq \frac{h}{4\pi}$$

Sample Problem 7.5 **Applying the Uncertainty Principle**

PROBLEM: An electron moving near an atomic nucleus has a speed $6\times10^6 \pm 1\%$. What is the uncertainty in its position (Δx)?

PLAN: The uncertainty (Δx) is given as ±1% (0.01) of 6×10^6 m/s. Once we calculate this, plug it into the uncertainty equation.

SOLUTION:

$$\Delta u = (0.01)(6\times10^6\ \text{m/s}) = 6\times10^4\ \text{m/s}$$

$$\Delta x \ * \ m\,\Delta u \geq \frac{h}{4\pi}$$

$$\Delta x \geq \frac{6.626\times10^{-34}\ \text{kg*m}^2\text{/s}}{4\pi\,(9.11\times10^{-31}\ \text{kg})(6\times10^4\ \text{m/s})} \geq 1 \times 10^{-9}\ \text{m}$$