# CHAPTER 8 IN REVIEW

## TERMS

### Section 8.1
quantum-mechanical model (312)

### Section 8.2
electromagnetic radiation (313)
amplitude (314)
wavelength ($\lambda$) (314)
frequency ($\nu$) (314)
electromagnetic spectrum (315)
gamma ($\gamma$) rays (316)
X-rays (316)
ultraviolet (UV) radiation (316)
visible light (316)
infrared (IR) radiation (316)
microwaves (316)
radio waves (316)
interference (317)
constructive interference (317)
destructive interference (318)
diffraction (318)
photoelectric effect (318)
photon (quantum) (320)

### Section 8.3
emission spectrum (323)

### Section 8.4
de Broglie relation (327)
complementary properties (329)
Heisenberg's uncertainty principle (329)
deterministic (330)
indeterminacy (330)

### Section 8.5
orbital (331)
wave function (331)
quantum number (331)
principal quantum number ($n$) (331)
angular momentum quantum number ($l$) (331)
magnetic quantum number ($m_l$) (331)
spin quantum number ($m_s$) (331)
principal level (shell) (333)
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### Section 8.6
probability density (337)
radial distribution function (338)
node (340)
phase (341)

## CONCEPTS

### The Realm of Quantum Mechanics (8.1)
- The theory of quantum mechanics explains the behavior of particles, such as photons (particles of light) and electrons, in the atomic and subatomic realms.
- Since the electrons of an atom determine many of its chemical and physical properties, quantum mechanics is foundational to understanding chemistry.

### The Nature of Light (8.2)
- Light is a type of electromagnetic radiation—a form of energy embodied in oscillating electric and magnetic fields that travels through space at $3.00 \times 10^8$ m/s.
- The wave nature of light is characterized by its wavelength—the distance between wave crests—and its ability to experience interference (constructive or destructive) and diffraction.
- The particle nature of light is characterized by the specific quantity of energy carried in each photon.
- The electromagnetic spectrum includes all wavelengths of electromagnetic radiation from gamma rays (high energy per photon, short wavelength) to radio waves (low energy per photon, long wavelength). Visible light is a tiny sliver in the middle of the electromagnetic spectrum.

### Atomic Spectroscopy (8.3)
- Atomic spectroscopy is study of the light absorbed and emitted by atoms when an electron makes a transition from one energy level to another.
- The wavelengths absorbed or emitted in atomic spectra depend on the energy differences between the levels involved in the transition; large energy differences result in short wavelengths, and small energy differences result in long wavelengths.

### The Wave Nature of Matter (8.4)
- Electrons have a wave nature with an associated wavelength; the de Broglie relation quantifies the wavelength of an electron.
- The wave nature and particle nature of matter are complementary—the more we know of one, the less we know of the other.
- The wave–particle duality of electrons is quantified in Heisenberg's uncertainty principle, which states that there is a limit to how well we can know both the position of an electron (associated with the electron's particle nature) and the velocity times the mass of an electron (associated with the electron's wave nature)—the more accurately one is measured, the greater the uncertainty in measurement of the other.
- The inability to simultaneously know both the position and velocity of an electron results in indeterminacy, the inability to predict a trajectory for an electron. Consequently, electron behavior is described differently than the behavior of everyday-sized particles.
- The trajectory we normally associate with macroscopic objects is replaced, for electrons, with statistical descriptions that show not the electron's path, but the region where it is most likely to be found.

### The Quantum-Mechanical Model of the Atom (8.5, 8.6)
- The most common way to describe electrons in atoms according to quantum mechanics is to solve the Schrödinger equation for the energy states of the electrons within the atom. When the electron is in these states, its energy is well defined but its position is not. The position of an electron is described by a probability distribution map called an orbital.
- The solutions to the Schrödinger equation (including the energies and orbitals) are characterized by four quantum numbers: $n$, $l$, $m_l$, and $m_s$.
- The principal quantum number ($n$) determines the energy of the electron and the size of the orbital; the angular momentum quantum number ($l$) determines the shape of the orbital; the magnetic quantum number ($m_l$) determines the orientation of the orbital; and the spin quantum number ($m_s$) specifies the orientation of the spin of the electron.

## EQUATIONS AND RELATIONSHIPS

Relationship between Frequency ($\nu$), Wavelength ($\lambda$), and the Speed of Light ($c$) (**8.2**)

$$\nu = \frac{c}{\lambda}$$

Relationship between Energy ($E$), Frequency ($\nu$), Wavelength ($\lambda$), and Planck's Constant ($h$) (**8.2**)

$$E = h\nu$$

$$E = \frac{hc}{\lambda}$$

De Broglie Relation: Relationship between Wavelength ($\lambda$), Mass ($m$), and Velocity ($v$) of a Particle (**8.4**)

$$\lambda = \frac{h}{mv}$$

Heisenberg's Uncertainty Principle: Relationship between a Particle's Uncertainty in Position ($\Delta x$) and Uncertainty in Velocity ($\Delta v$) (**8.4**)

$$\Delta x \times m\Delta v \geq \frac{h}{4\pi}$$

Energy of an Electron in an Orbital with Quantum Number $n$ in a Hydrogen Atom (**8.5**)

$$E_n = -2.18 \times 10^{-18}\ \text{J}\left(\frac{1}{n^2}\right) \quad (n = 1, 2, 3, \ldots)$$

Change in Energy That Occurs in an Atom When It Undergoes a Transition between Levels $n_{\text{initial}}$ and $n_{\text{final}}$ (**8.5**)

$$\Delta E = -2.18 \times 10^{-18}\ \text{J}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

## LEARNING OUTCOMES

| Chapter Objectives | Assessment |
|---|---|
| Analyze the wave properties and wave behaviors associated with light (**8.2**) | Example 8.1 **For Practice** 8.1 **Exercises** 35–36, 39–40 |
| Analyze the particle properties and particle behaviors associated with light (**8.2**) | Examples 8.2, 8.3 **For Practice** 8.2, 8.3 **For More Practice** 8.2 **Exercises** 37–38, 41–46 |
| Analyze the wave properties of matter (**8.4**) | Example 8.4 **For Practice** 8.4 **Exercises** 47–56 |
| Describe orbitals using quantum numbers (**8.5**) | Examples 8.5, 8.6 **For Practice** 8.5, 8.6 **Exercises** 57–64 |
| Calculate the energy change of an electron transition according to the Bohr model (**8.5**) | Example 8.7 **For Practice** 8.7 **For More Practice** 8.7 **Exercises** 65–72 |

## EXERCISES

**Mastering Chemistry** provides end-of-chapter exercises, feedback-enriched tutorial problems, animations, and interactive activities to encourage problem-solving practice and deeper understanding of key concepts and topics.

## REVIEW QUESTIONS

**1.** Why is the quantum-mechanical model of the atom important for understanding chemistry?

**2.** What is light? How fast does it travel in a vacuum?

**3.** Define the wavelength and amplitude of a wave. How are these related to the energy of the wave?

**4.** Define the frequency of electromagnetic radiation. How is frequency related to wavelength?

**5.** What determines the color of light? Describe the difference between red light and blue light.

**6.** What determines the color of a colored object? Explain why grass appears green.

**7.** Give an approximate range of wavelengths for each type of electromagnetic radiation and summarize the characteristics and/or the uses of each.

- **a.** gamma rays
- **b.** X-rays
- **c.** ultraviolet radiation
- **d.** visible light
- **e.** infrared radiation
- **f.** microwave radiation
- **g.** radio waves

**8.** Explain the wave behavior known as interference. Explain the difference between constructive and destructive interference.

**9.** Explain the wave behavior known as diffraction. Draw the diffraction pattern that occurs when light travels through two slits comparable in size and separation to the light's wavelength.

**10.** Describe the photoelectric effect. How did experimental observations of this phenomenon differ from the predictions of classical electromagnetic theory?

**11.** How did the photoelectric effect lead Einstein to propose that light is quantized?

**12.** What is a photon? How is the energy of a photon related to its wavelength? Its frequency?

**13.** What is an emission spectrum? How does an emission spectrum of a gas in a discharge tube differ from a white light spectrum?

**14.** Describe the Bohr model for the atom. How did the Bohr model account for the emission spectra of atoms?

**15.** Explain electron diffraction.

**16.** What is the de Broglie wavelength of an electron? What determines the value of the de Broglie wavelength for an electron?

**17.** What are complementary properties? How does electron diffraction demonstrate the complementarity of the wave nature and particle nature of the electron?

**18.** Explain Heisenberg's uncertainty principle. What paradox is at least partially solved by the uncertainty principle?

**19.** What is a trajectory? What kind of information do you need to predict the trajectory of a particle?

**20.** Why does the uncertainty principle make it impossible to predict a trajectory for the electron?

**21.** Newton's laws of motion are *deterministic*. Explain this statement.

**22.** An electron behaves in ways that are at least partially indeterminate. Explain this statement.

**23.** What is a probability distribution map?

**24.** For each solution to the Schrödinger equation, what can be precisely specified: the electron's energy or its position? Explain.

**25.** What is a quantum-mechanical orbital?

**26.** What is the Schrödinger equation? What is a wave function? How is a wave function related to an orbital?

**27.** What are the possible values of the principal quantum number $n$? What does the principal quantum number determine?

**28.** What are the possible values of the angular momentum quantum number $l$? What does the angular momentum quantum number determine?

**29.** What are the possible values of the magnetic quantum number $m_l$? What does the magnetic quantum number determine?

**30.** List all the orbitals in each principal level. Specify the three quantum numbers for each orbital.

**a.** $n = 1$ **b.** $n = 2$ **c.** $n = 3$ **d.** $n = 4$

**31.** Explain the difference between a plot showing the probability density for an orbital and one showing the radial distribution function.

**32.** Make sketches of the general shapes of the *s, p,* and *d* orbitals.

**33.** List the four different sublevels associated with $n = 4$. Given that only a maximum of two electrons can occupy an orbital, determine the maximum number of electrons that can exist in each sublevel.

**34.** Why are atoms usually portrayed as spheres when most orbitals are not spherically shaped?

# PROBLEMS BY TOPIC

## Electromagnetic Radiation

**35.** The distance from the sun to Earth is $1.496 \times 10^8$ km. How long does it take light to travel from the sun to Earth?
**MISSED THIS?** *Read Section 8.2*

**36.** The nearest star to our sun is Proxima Centauri, at a distance of 4.3 light-years from the sun. A light-year is the distance that light travels in one year (365 days). How far away, in km, is Proxima Centauri from the sun?

**37.** List these types of electromagnetic radiation in order of (i) increasing wavelength and (ii) increasing energy per photon.
**MISSED THIS?** *Read Section 8.2; Watch KCV 8.2, IWE 8.3*

**a.** radio waves **b.** microwaves
**c.** infrared radiation **d.** ultraviolet radiation

**38.** List these types of electromagnetic radiation in order of (i) increasing frequency and (ii) decreasing energy per photon.

**a.** gamma rays **b.** radio waves
**c.** microwaves **d.** visible light

**39.** Calculate the frequency of each wavelength of electromagnetic radiation. **MISSED THIS?** *Read Section 8.2*

**a.** 632.8 nm (wavelength of red light from helium–neon laser)
**b.** 503 nm (wavelength of maximum solar radiation)
**c.** 0.052 nm (a wavelength contained in medical X-rays)

**40.** Calculate the wavelength of each frequency of electromagnetic radiation.

**a.** 100.2 MHz (typical frequency for FM radio broadcasting)
**b.** 1070 kHz (typical frequency for AM radio broadcasting) (assume four significant figures)
**c.** 835.6 MHz (common frequency used for cell phone communication)

**41.** Calculate the energy of a photon of electromagnetic radiation at each of the wavelengths indicated in Problem 39.
**MISSED THIS?** *Read Section 8.2; Watch KCV 8.2, IWE 8.2*

**42.** Calculate the energy of a photon of electromagnetic radiation at each of the frequencies indicated in Problem 40.

**43.** A laser pulse with wavelength 532 nm contains 3.85 mJ of energy. How many photons are in the laser pulse?
**MISSED THIS?** *Read Section 8.2; Watch KCV 8.2, IWE 8.2*

**44.** A heat lamp produces 32.8 watts of power at a wavelength of 6.5 $\mu$m. How many photons are emitted per second? (1 watt = 1 J/s)

**45.** Determine the energy of 1 mol of photons for each kind of light. (Assume three significant figures.)
**MISSED THIS?** *Read Section 8.2; Watch KCV 8.2, IWE 8.2*

**a.** infrared radiation (1500 nm)
**b.** visible light (500 nm)
**c.** ultraviolet radiation (150 nm)

**46.** How much energy is contained in 1 mol of each?

**a.** X-ray photons with a wavelength of 0.135 nm
**b.** $\gamma$-ray photons with a wavelength of $2.15 \times 10^{-5}$ nm

## The Wave Nature of Matter and the Uncertainty Principle

**47.** Sketch the interference pattern that results from the diffraction of electrons passing through two closely spaced slits.
**MISSED THIS?** *Read Section 8.4; Watch KCV 8.4*

**48.** What happens to the interference pattern described in Problem 47 if the rate of electrons going through the slits is decreased to one electron per hour? What happens to the pattern if we try to determine which slit the electron goes through by using a laser placed directly behind the slits?

**49.** The resolution limit of a microscope is roughly equal to the wavelength of light used in producing the image. Electron microscopes use an electron beam (in place of photons) to produce much higher resolution images, about 0.20 nm in modern instruments. Assuming that the resolution of an electron microscope is equal to the de Broglie wavelength of the electrons used, to what speed must the electrons be accelerated to obtain a resolution of 0.20 nm?
**MISSED THIS?** *Read Section 8.4; Watch KCV 8.4*

**50.** The smallest atoms can themselves exhibit quantum-mechanical behavior. Calculate the de Broglie wavelength (in pm) of a hydrogen atom traveling at 475 m/s.

**51.** What is the de Broglie wavelength of an electron traveling at $1.35 \times 10^5$ m/s? **MISSED THIS?** *Read Section 8.4; Watch KCV 8.4*

**52.** A proton in a linear accelerator has a de Broglie wavelength of 122 pm. What is the speed of the proton?

**53.** Calculate the de Broglie wavelength of a 143-g baseball traveling at 95 mph. Why is the wave nature of matter not important for a baseball? **MISSED THIS?** *Read Section 8.4; Watch KCV 8.4*

**54.** A 0.22-caliber handgun fires a 1.9-g bullet at a velocity of 765 m/s. Calculate the de Broglie wavelength of the bullet. Is the wave nature of matter significant for bullets?

**55.** An electron has an uncertainty in its position of 552 pm. What is the minimum uncertainty in its velocity?
**MISSED THIS?** *Read Section 8.4*

**56.** An electron traveling at $3.7 \times 10^5$ m/s has an uncertainty in its velocity of $1.88 \times 10^5$ m/s. What is the minimum uncertainty in its position?

## Orbitals and Quantum Numbers

**57.** Which electron is, on average, closer to the nucleus: an electron in a 2*s* orbital or an electron in a 3*s* orbital?
**MISSED THIS?** *Read Sections 8.5, 8.6; Watch KCV 8.5A*

**58.** Which electron is, on average, farther from the nucleus: an electron in a 3*p* orbital or an electron in a 4*p* orbital?

**59.** What are the possible values of $l$ for each value of $n$?
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5A*

**a.** 1 **b.** 2 **c.** 3 **d.** 4

**60.** What are the possible values of $m_l$ for each value of $l$?

**a.** 0 **b.** 1 **c.** 2 **d.** 3

**61.** Which set of quantum numbers *cannot* specify an orbital?
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5A, IWE 8.5*

**a.** $n = 2, l = 1, m_l = -1$ **b.** $n = 3, l = 2, m_l = 0$
**c.** $n = 3, l = 3, m_l = 2$ **d.** $n = 4, l = 3, m_l = 0$

**62.** Which combinations of $n$ and $l$ represent real orbitals, and which do not exist?

**a.** 1*s* **b.** 2*p* **c.** 4*s* **d.** 2*d*

**63.** Sketch the 1*s* and 2*p* orbitals. How do the 2*s* and 3*p* orbitals differ from the 1*s* and 2*p* orbitals? **MISSED THIS?** *Read Section 8.6*

**64.** Sketch the 3*d* orbitals. How do the 4*d* orbitals differ from the 3*d* orbitals?

## Atomic Spectroscopy

**65.** An electron in a hydrogen atom is excited with electrical energy to an excited state with $n = 2$. The atom then emits a photon. What is the value of $n$ for the electron following the emission?
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5B*

**66.** Determine whether each transition in the hydrogen atom corresponds to absorption or emission of energy.

**a.** $n = 3 \longrightarrow n = 1$
**b.** $n = 2 \longrightarrow n = 4$
**c.** $n = 4 \longrightarrow n = 3$

**67.** According to the quantum-mechanical model for the hydrogen atom, which electron transition produces light with the longer wavelength: $2p \longrightarrow 1s$ or $3p \longrightarrow 1s$?
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5B*

**68.** According to the quantum-mechanical model for the hydrogen atom, which electron transition produces light with the longer wavelength: $3p \longrightarrow 2s$ or $4p \longrightarrow 3p$?

**69.** Calculate the wavelength of the light emitted when an electron in a hydrogen atom makes each transition and indicate the region of the electromagnetic spectrum (infrared, visible, ultraviolet, etc.) where the light is found.
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5B, IWE 8.7*

**a.** $n = 2 \longrightarrow n = 1$ **b.** $n = 3 \longrightarrow n = 1$
**c.** $n = 4 \longrightarrow n = 2$ **d.** $n = 5 \longrightarrow n = 2$

**70.** Calculate the frequency of the light emitted when an electron in a hydrogen atom makes each transition.

**a.** $n = 4 \longrightarrow n = 3$ **b.** $n = 5 \longrightarrow n = 1$
**c.** $n = 5 \longrightarrow n = 4$ **d.** $n = 6 \longrightarrow n = 5$

**71.** An electron in the $n = 7$ level of the hydrogen atom relaxes to a lower energy level, emitting light of 397 nm. What is the value of $n$ for the level to which the electron relaxed?
**MISSED THIS?** *Read Section 8.5; Watch KCV 8.5B, IWE 8.7*

**72.** An electron in a hydrogen atom relaxes to the $n = 4$ level, emitting light of 114 THz. What is the value of $n$ for the level in which the electron originated?

# CUMULATIVE PROBLEMS

**73.** Ultraviolet radiation and radiation of shorter wavelengths can damage biological molecules because these kinds of radiation carry enough energy to break bonds within the molecules. A typical carbon–carbon bond requires 348 kJ/mol to break. What is the longest wavelength of radiation with enough energy to break carbon–carbon bonds?

**74.** The human eye contains a molecule called 11-*cis*-retinal that changes shape when struck with light of sufficient energy. The change in shape triggers a series of events that result in an electrical signal being sent to the brain that results in vision. The minimum energy required to change the conformation of 11-*cis*-retinal within the eye is about 164 kJ/mol. Calculate the longest wavelength visible to the human eye.

**75.** An argon ion laser puts out 5.0 W of continuous power at a wavelength of 532 nm. The diameter of the laser beam is 5.5 mm. If the laser is pointed toward a pinhole with a diameter of 1.2 mm, how many photons travel through the pinhole per second? Assume that the light intensity is equally distributed throughout the entire cross-sectional area of the beam. (1 W = 1 J/s)

**76.** A green leaf has a surface area of $2.50\ cm^2$. If solar radiation is $1000\ W/m^2$, how many photons strike the leaf every second? Assume three significant figures and an average wavelength of 504 nm for solar radiation.

**77.** In a technique used for surface analysis called Auger electron spectroscopy (AES), electrons are accelerated toward a metal surface. These electrons cause the emissions of secondary electrons—called Auger electrons—from the metal surface. The kinetic energy of the Auger electrons depends on the composition of the surface. The presence of oxygen atoms on the surface results in Auger electrons with a kinetic energy of approximately 506 eV. What is the de Broglie wavelength of one of these electrons?

$$[\text{KE} = \tfrac{1}{2}mv^2; 1 \text{ electron volt (eV)} = 1.602 \times 10^{-19}\,\text{J}]$$

**78.** An X-ray photon of wavelength 0.989 nm strikes a surface. The emitted electron has a kinetic energy of 969 eV. What is the binding energy of the electron in kJ/mol?

$$[1 \text{ electron volt (eV)} = 1.602 \times 10^{-19}\,\text{J}]$$

**79.** Ionization involves completely removing an electron from an atom. How much energy is required to ionize a hydrogen atom in its ground (or lowest energy) state? What wavelength of light contains enough energy in a single photon to ionize a hydrogen atom?

**80.** The energy required to ionize sodium is 496 kJ/mol. What minimum frequency of light is required to ionize sodium?

**81.** Suppose that in an alternate universe, the possible values of $l$ are the integer values from 0 to $n$ (instead of 0 to $n - 1$). Assuming no other differences between this imaginary universe and ours, how many orbitals exist in each level in the alternate universe?

**a.** $n = 1$ **b.** $n = 2$ **c.** $n = 3$

**82.** Suppose that, in an alternate universe, the possible values of $m_l$ are the integer values including 0 ranging from $-l - 1$ to $l + 1$ (instead of simply $-l$ to $+l$). How many orbitals exist in each sublevel in the alternate universe?

**a.** $s$ sublevel **b.** $p$ sublevel **c.** $d$ sublevel

**83.** An atomic emission spectrum of hydrogen shows three wavelengths: 1875 nm, 1282 nm, and 1093 nm. Assign these wavelengths to transitions in the hydrogen atom.

**84.** An atomic emission spectrum of hydrogen shows three wavelengths: 121.5 nm, 102.6 nm, and 97.23 nm. Assign these wavelengths to transitions in the hydrogen atom.

**85.** The binding energy of electrons in a metal is 193 kJ/mol. Find the threshold frequency of the metal.

**86.** In order for a thermonuclear fusion reaction of two deuterons ($^2_1H^+$) to take place, the deuterons must collide and each must have a velocity of about $1 \times 10^6$ m/s. Find the wavelength of such a deuteron.

**87.** The speed of sound in air is 344 m/s at room temperature. The lowest frequency of a large organ pipe is 30 $s^{-1}$ and the highest frequency of a piccolo is $1.5 \times 10^4\,s^{-1}$. Find the difference in wavelength between these two sounds.

**88.** The distance from Earth to the sun is $1.5 \times 10^8$ km. Find the number of crests in a light wave of frequency $1.0 \times 10^{14}\,s^{-1}$ traveling from the sun to Earth.

**89.** The iodine molecule can be photodissociated (broken apart with light) into iodine atoms in the gas phase with light of wavelengths shorter than about 792 nm. A 100.0-mL glass tube contains 55.7 mtorr of gaseous iodine at 25.0 °C. What minimum amount of light energy must be absorbed by the iodine in the tube to dissociate 15.0% of the molecules?

**90.** A 5.00-mL ampule of a 0.100-M solution of naphthalene in hexane is excited with a flash of light. The naphthalene emits 15.5 J of energy at an average wavelength of 349 nm. What percentage of the naphthalene molecules emitted a photon?

**91.** A laser produces 20.0 mW of red light. In 1.00 hr, the laser emits $2.29 \times 10^{20}$ photons. What is the wavelength of the laser?

**92.** A particular laser consumes 150.0 watts of electrical power and produces a stream of $1.33 \times 10^{19}$ 1064-nm photons per second. What is the percent efficiency of the laser in converting electrical power to light?

**93.** The quantum yield of light-induced chemical reactions (called photochemical reactions) measures the efficiency of the process. The quantum yield, $\phi$, is defined as: $\phi = \dfrac{\text{number of reaction events}}{\text{number of photons absorbed}}$. Suppose the quantum yield for the reaction $CH_3X \longrightarrow CH_3 + X$ is $\phi = 0.24$. A cuvette containing a solution of $CH_3X$ is irradiated with 280-nm light with a power of 885 mW for 10.0 minutes. Assuming total absorption of the light by the sample, what is the maximum amount (in moles) of $CH_3X$ that breaks apart?

**94.** A student is studying the photodissociation (dissociation with light) of $I_2 \longrightarrow 2\,I$. When a sample of $I_2$ is irradiated with a power of 255 mW at 590 nm for 35 seconds, 0.0256 mmol of I forms. Assuming complete absorption of the incident radiation, what is the quantum yield, $\phi$, of the reaction? (See Problem 93 for definition of quantum yield.)

## CHALLENGE PROBLEMS

**95.** An electron confined to a one-dimensional box has energy levels given by the equation:

$$E_n = n^2h^2/8\,mL^2$$

where $n$ is a quantum number with possible values of 1, 2, 3, . . . , $m$ is the mass of the particle, and $L$ is the length of the box.

**a.** Calculate the energies of the $n = 1$, $n = 2$, and $n = 3$ levels for an electron in a box with a length of 155 pm.

**b.** Calculate the wavelength of light required to make a transition from $n = 1 \longrightarrow n = 2$ from $n = 2 \longrightarrow n = 3$. In what region of the electromagnetic spectrum do these wavelengths lie?

**96.** The energy of a vibrating molecule is quantized much like the energy of an electron in the hydrogen atom. The energy levels of a vibrating molecule are given by the equation:

$$E_n = \left(n + \frac{1}{2}\right)h\nu$$

where $n$ is a quantum number with possible values of 1, 2, . . . , and $\nu$ is the frequency of vibration. The vibration frequency of HCl is approximately $8.85 \times 10^{13}\,s^{-1}$. What minimum energy is required to excite a vibration in HCl? What wavelength of light is required to excite this vibration?

**97.** The wave functions for the 1$s$ and 2$s$ orbitals are as follows:

$$1s \quad \psi = (1/\pi)^{1/2}(1/a_0^{3/2})\exp(-r/a_0)$$

$$2s \quad \psi = (1/32\pi)^{1/2}(1/a_0^{3/2})(2 - r/a_0)\exp(-r/2a_0)$$

where $a_0$ is a constant ($a_0 = 53$ pm) and $r$ is the distance from the nucleus. Use a spreadsheet to make a plot of each of these wave functions for values of $r$ ranging from 0 pm to 200 pm. Describe the differences in the plots and identify the node in the 2$s$ wave function.

**98.** Before quantum mechanics was developed, Johannes Rydberg developed an equation that predicted the wavelengths ($\lambda$) in the atomic spectrum of hydrogen:

$$1/\lambda = R(1/m^2 - 1/n^2)$$

In this equation, $R$ is a constant and $m$ and $n$ are integers. Use the quantum-mechanical model for the hydrogen atom to derive the Rydberg equation.

**99.** Find the velocity of an electron emitted by a metal with a threshold frequency of $2.25 \times 10^{14}\ s^{-1}$ when it is exposed to visible light of wavelength $5.00 \times 10^{-7}$ m.

**100.** Water is exposed to infrared radiation of wavelength $2.8 \times 10^{-4}$ cm. Assume that all the radiation is absorbed and converted to heat. How many photons are required to raise the temperature of 2.0 g of water by 2.0 K?

**101.** The 2005 Nobel Prize in Physics was given, in part, to scientists who had made ultrashort pulses of light. These pulses are important in making measurements involving very short time periods. One challenge in making such pulses is the uncertainty principle, which can be stated with respect to energy and time as $\Delta E \cdot \Delta t \geq h/4\pi$. What is the energy uncertainty ($\Delta E$) associated with a short pulse of laser light that lasts for only 5.0 femtoseconds (fs)? Suppose the low-energy end of the pulse had a wavelength of 722 nm. What is the wavelength of the high-energy end of the pulse that is limited only by the uncertainty principle?

**102.** A metal with a threshold frequency of $6.71 \times 10^{14}\ s^{-1}$ emits an electron with a velocity of $6.95 \times 10^{5}$ m/s when radiation of $1.01 \times 10^{15}\ s^{-1}$ strikes the metal. Calculate the mass of the electron.

**103.** Find the longest wavelength of a wave that can travel around in a circular orbit of radius 1.8 m.

**104.** The heat of fusion of ice is 6.00 kJ/mol. Find the number of photons of wavelength $= 6.42 \times 10^{-6}$ m that must be absorbed to melt 1.00 g of ice.

## CONCEPTUAL PROBLEMS

**105.** Explain the difference between the Bohr model for the hydrogen atom and the quantum-mechanical model. Is the Bohr model consistent with Heisenberg's uncertainty principle?

**106.** The light emitted from one of the following electronic transitions ($n = 4 \longrightarrow n = 3$ or $n = 3 \longrightarrow n = 2$) in the hydrogen atom causes the photoelectric effect in a particular metal, while light from the other transition does not. Which transition causes the photoelectric effect and why?

**107.** Determine whether an interference pattern is observed on the other side of the slits in each experiment.

**a.** An electron beam is aimed at two closely spaced slits. The beam produces only one electron per minute.

**b.** An electron beam is aimed at two closely spaced slits. A light beam is placed at each slit to determine when an electron goes through the slit.

**c.** A high-intensity light beam is aimed at two closely spaced slits.

**d.** A gun is fired at a solid wall containing two closely spaced slits. (Will the bullets that pass through the slits form an interference pattern on the other side of the solid wall?)

**108.** Which transition in the hydrogen atom produces emitted light with the longest wavelength?

**a.** $n = 4 \longrightarrow n = 3$

**b.** $n = 2 \longrightarrow n = 1$

**c.** $n = 3 \longrightarrow n = 2$

## QUESTIONS FOR GROUP WORK

*Active Classroom Learning*

Discuss these questions with the group and record your consensus answer.

**109.** Discuss the nature of light with your group. Ask each member of your group to transcribe one complete sentence about the physical nature of light.

**110.** How are electrons like baseballs? How are they unlike baseballs?

**111.** What are all the possible values of $m_l$ if $l = 0$ (an $s$ orbital)? If $l = 1$ (a $p$ orbital)? If $l = 2$ (a $d$ orbital)? How many possible values of $m_l$ would there be if $l = 20$? Write an equation to determine the number of possible values of $m_l$ from the value of $l$.

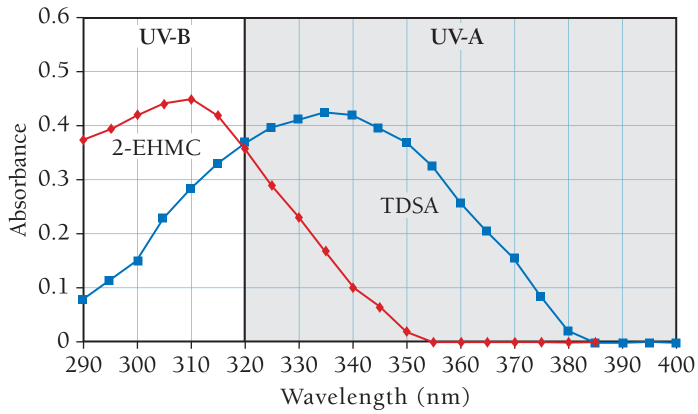
**112.** Have each group member choose a set of quantum numbers for an electron in a hydrogen atom. Calculate the wavelength of light produced if an electron moves from your state to each state of the other group members. Make a table comparing all possible combinations, and list all wavelengths in order of increasing energy.

**113.** How many nodes are there in the 1$s$, 2$p$, and 3$d$ orbitals? How many nodes are in a 4$f$ orbital?

# DATA INTERPRETATION AND ANALYSIS

## UV Radiation and Sunscreen

**114.** Sunscreen contains compounds that absorb ultraviolet light. When sunscreen is applied to skin, it prevents ultraviolet light from reaching the skin. The graph that follows shows the absorbance of light as a function of wavelength for two different compounds (2-EHMC and TDSA) common in sunscreen. Absorbance is a measure of the amount of light absorbed by the compound—the higher the absorbance, the more light is absorbed. Study the graph and answer the questions.




http://mycpss.com/critical-wavelength-broad-spectrum-uv-protection/

**a.** Calculate the energy of a photon at the maximum absorption of TDSA.

**b.** Calculate the energy of a photon at the maximum absorption of 2-EHMC.

**c.** Which compound absorbs more energy at its maximum absorption?

**d.** Why do you think sunscreens commonly contain both of these compounds and not just one of them?

**e.** Assuming that sunlight produces $3.066 \times 10^{22} \frac{\text{uv photons}}{\text{m}^2 \cdot \text{s}}$, and that the skin absorbs one-half of these photons (and reflects the other half) calculate the total uv energy absorbed over 0.42 $m^2$ of skin that is exposed to sunlight for one hour. Assume that the average wavelength of the uv photons is 330 nm.

# ANSWERS TO CONCEPTUAL CONNECTIONS

### Wave Nature of Light

**8.1** **(c)** Since the light emitted from the lasers have different colors, they must also have different frequencies. The brighter the light, the greater its amplitude, so the bright green laser emits light with a greater amplitude than the dim red one.

### Frequency of Light

**8.2** **(a)** As you can see in the electromagnetic spectrum, infrared has the longest wavelength of the three types of electromagnetic radiation listed and X-rays have the shortest.

### The Photoelectric Effect

**8.3** **(b)** The 325-nm light has the shortest wavelength of light (highest energy per photon) and corresponds to the photoelectrons with the greatest kinetic energy.

### The de Broglie Wavelength of Macroscopic Objects

**8.4** **(a)** Because of the baseball's large mass, its de Broglie wavelength is minuscule. (For a 150-g baseball, $\lambda$ is on the order of $10^{-34}$ m.) This minuscule wavelength is insignificant compared to the size of the baseball itself, and therefore its effects are not observable.

### The Uncertainty Principle

**8.5** **(b)** The uncertainty principle states that the position and velocity of an electron cannot be simultaneously known. Position and velocity are complementary: the more precisely you know one quantity, the less precisely you know the other.

### The Relationship between *n* and *l*

**8.6** **(c)** Since $l$ can have a maximum value of $n - 1$ and since $n = 3$, $l$ can have a maximum value of 2.

### The Relationship between *l* and $m_l$

**8.7** **(d)** Since $m_l$ can have the integer values (including 0) between $-l$ and $+l$ and since $l = 2$, the possible values of $m_l$ are $-2, -1, 0, +1$, and $+2$.

### Emission Spectra

**8.8** **(c)** The energy difference between $n = 3$ and $n = 2$ is greatest because the energy differences become closer together with increasing $n$. The greater energy difference results in an emitted photon of greater energy and therefore shorter wavelength.