CHEMISTRY

Matter and Change

Chapter 5: Electrons in Atoms

McGraw Hill Education

Click the mouse button or press the space bar to continue.

Table Of Contents

Click a hyperlink to view the corresponding slides.

Exit

Objectives

- **Compare** the wave and particle natures of light.
- **Define** a quantum of energy, and explain how it is related to an energy change of matter.
- **Contrast** continuous electromagnetic spectra and atomic emission spectra.

Review Vocabulary

radiation: the rays and particles —alpha particles, beta particles, and gamma rays—that are emitted by radioactive material

Light and Quantized Energy

New Vocabulary

- electromagnetic radiation
- wavelength
- frequency
- amplitude
- electromagnetic spectrum
- quantum
- Planck's constant
- photoelectric effect
- photon
- atomic emission spectrum

MAIN Idea **Light, a form of electronic radiation, has characteristics of both a wave and a particle.**

The Atom and Unanswered Questions

- Recall that in Rutherford's model, the atom's mass is concentrated in the nucleus and electrons move around it.
- The model doesn't explain how the electrons were arranged around the nucleus.
- The model doesn't explain why negatively charged electrons aren't pulled into the the positively charged nucleus.

The Atom and Unanswered Questions (cont.)

- In the early 1900s, scientists observed certain elements emitted visible light when heated in a flame.

Light and Quantized Energy

- Analysis of the emitted light revealed that an element's chemical behavior is related to the arrangement of the electrons in its atoms.

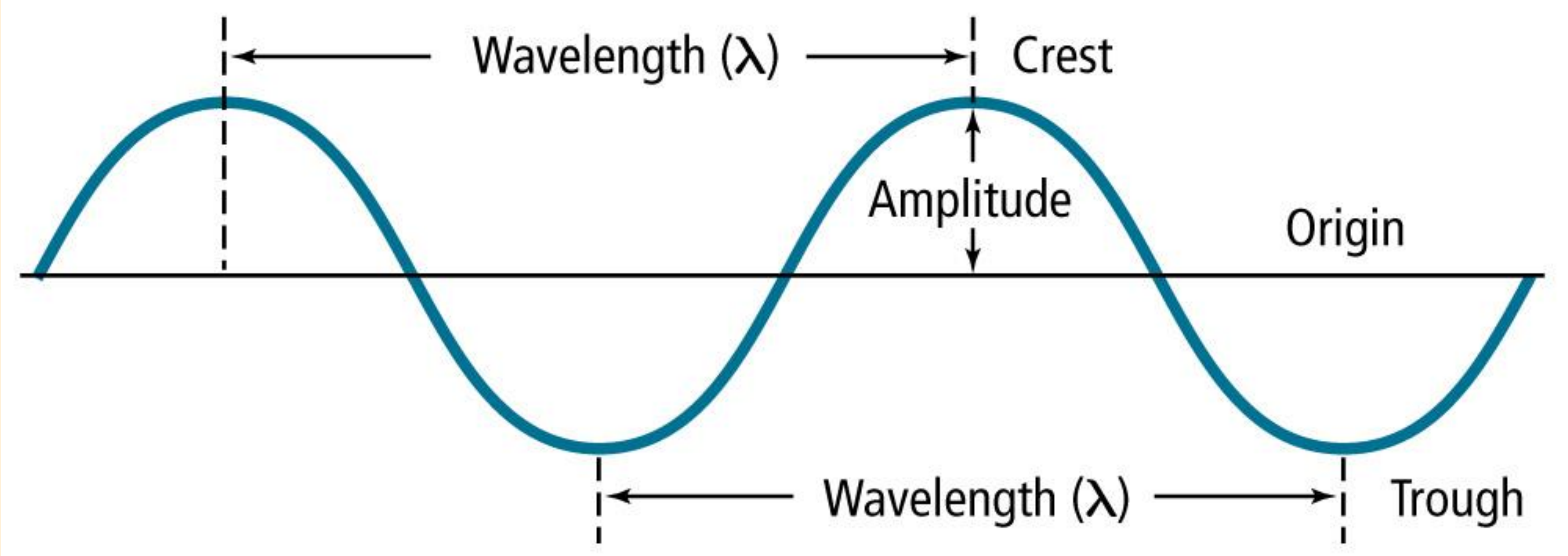
The Wave Nature of Light

- Visible light is a type of **electromagnetic radiation**, a form of energy that exhibits wave-like behavior as it travels through space.
- All waves can be described by several characteristics.

The Wave Nature of Light (cont.)

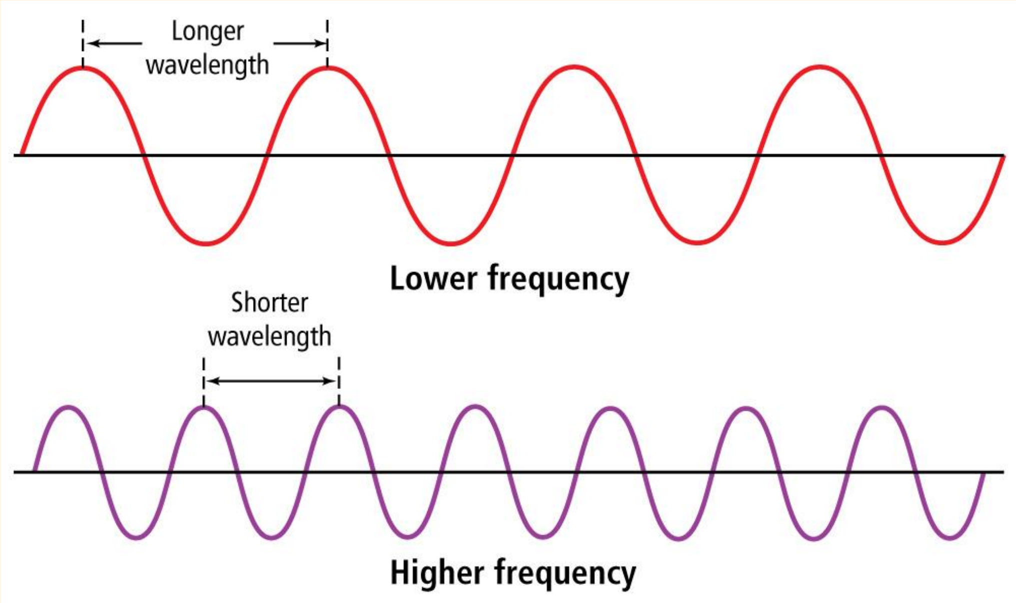
- The **wavelength** (λ) is the shortest distance between equivalent points on a continuous wave.
- The **frequency** (ν) is the number of waves that pass a given point per second.
- The **amplitude** is the wave's height from the origin to a crest.

The Wave Nature of Light (cont.)



The Wave Nature of Light (cont.)

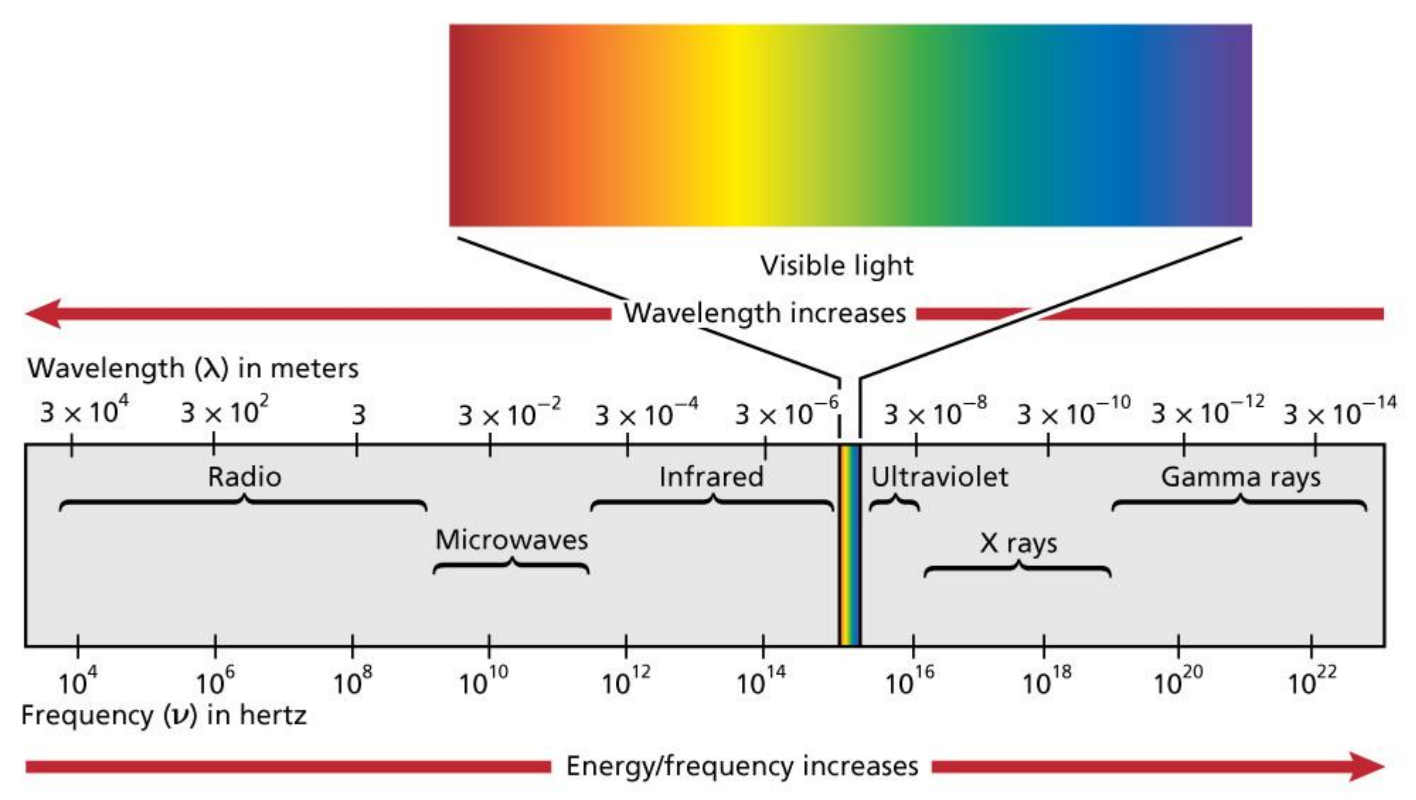
- The speed of light (3.00×10^8 m/s) is the product of it's wavelength and frequency $c = \lambda\nu$.



The Wave Nature of Light (cont.)

- Sunlight contains a continuous range of wavelengths and frequencies.
- A prism separates sunlight into a continuous spectrum of colors.
- The **electromagnetic spectrum** includes all forms of electromagnetic radiation.

The Wave Nature of Light (cont.)



Electromagnetic Spectrum

The Particle Nature of Light

- The wave model of light cannot explain all of light's characteristics.
  - **Ex.** Why heated objects emit only certain frequencies of light at a given temperature.
- In 1900, German physicist Max Planck (1858-1947) began searching for an explanation of this phenomenon as he studied the light emitted by heated objects.

The Particle Nature of Light (Cont.)

- Planck's study led him to a startling conclusion:
  - –Matter can gain or lose energy only in small, specific amounts called quanta.
  - –A **quantum** is the minimum amount of energy that can be gained or lost by an atom.

Energy of a Quantum

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

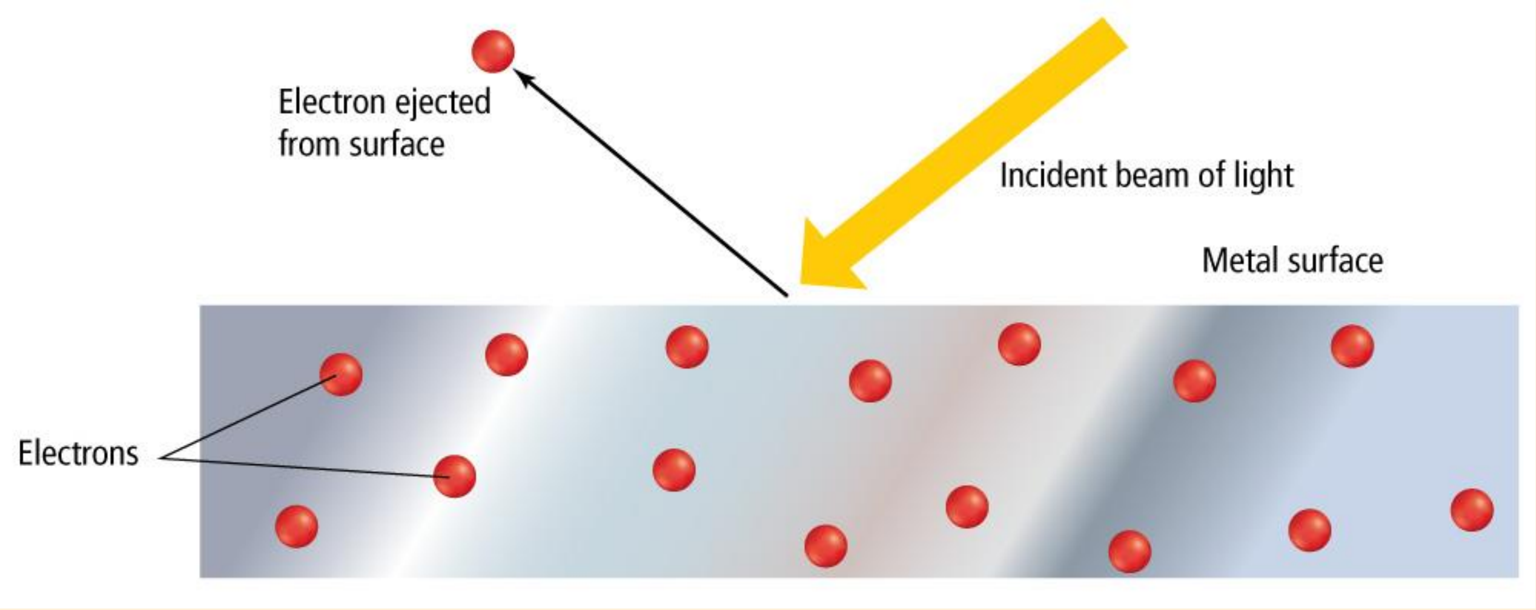
$E_{quantum}$ represents energy.
h is Planck's constant.
ν represents frequency.

The energy of a quantum is given by the product of Planck's constant and the frequency.

  - –**Planck's constant** has a value of 6.626 × 10–34 J ● s.

The Particle Nature of Light (Cont.)

- The **photoelectric effect** is when electrons are emitted from a metal's surface when light of a certain frequency shines on it.



The Particle Nature of Light (Cont.)

- Albert Einstein proposed in 1905 that light has a dual nature.
  - –A beam of light has wavelike and particlelike properties.
  - –A **photon** is a particle of electromagnetic radiation with no mass that carries a quantum of energy.

Energy of a Photon

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

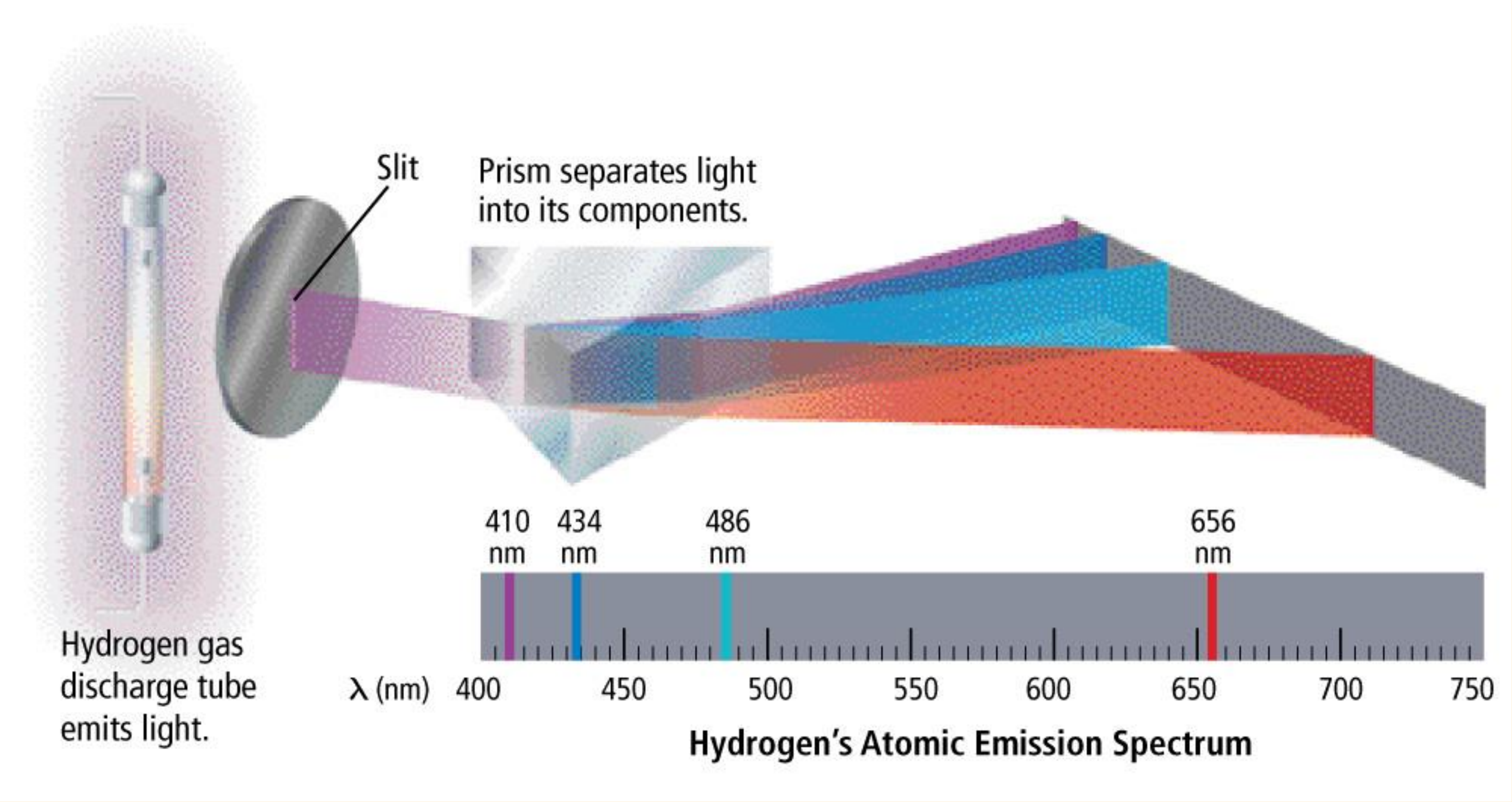
E_{photon} represents energy.
h is Planck's constant.
ν represents frequency.

The energy of a photon is given by the product of Planck's constant and the frequency.

Atomic Emission Spectra

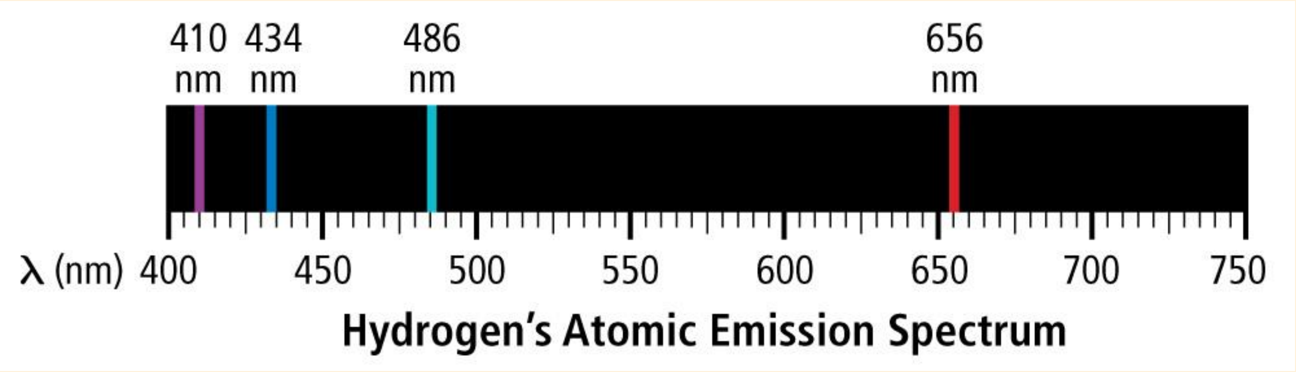
- Light in a neon sign is produced when electricity is passed through a tube filled with neon gas and excites the neon atoms.
- The excited atoms return to their stable state by emitting light to release energy.

Atomic Emission Spectra (cont.)



Atomic Emission Spectra (cont.)

- The **atomic emission spectrum** of an element is the set of frequencies of the electromagnetic waves emitted by the atoms of the element.
- Each element's atomic emission spectrum is unique.



Section Check

What is the smallest amount of energy that can be gained or lost by an atom?

A. electromagnetic photon

B. beta particle

C. quanta

D. wave-particle

What is a particle of electromagnetic radiation with no mass called?

A. beta particle

B. alpha particle

C. quanta

D. photon

Click here to go back to the chapter menu.

Click the mouse button or press the space bar to continue.

Objectives

- **Compare** the Bohr and quantum mechanical models of the atom.
- **Explain** the impact of de Broglie's wave article duality and the Heisenberg uncertainty principle on the current view of electrons in atoms.
- **Identify** the relationships among a hydrogen atom's energy levels, sublevels, and atomic orbitals.

Review Vocabulary

atom: the smallest particle of an element that retains all the properties of that element, is composed of electrons, protons, and neutrons.

Quantum Theory and the Atom

New Vocabulary

ground state

quantum number

de Broglie equation

Heisenberg uncertainty principle

quantum mechanical model of the atom

atomic orbital

principal quantum number

principal energy level

energy sublevel

MAIN Idea **Wavelike properties of electrons help relate atomic emission spectra, energy states of atoms, and atomic orbitals.**

Bohr's Model of the Atom

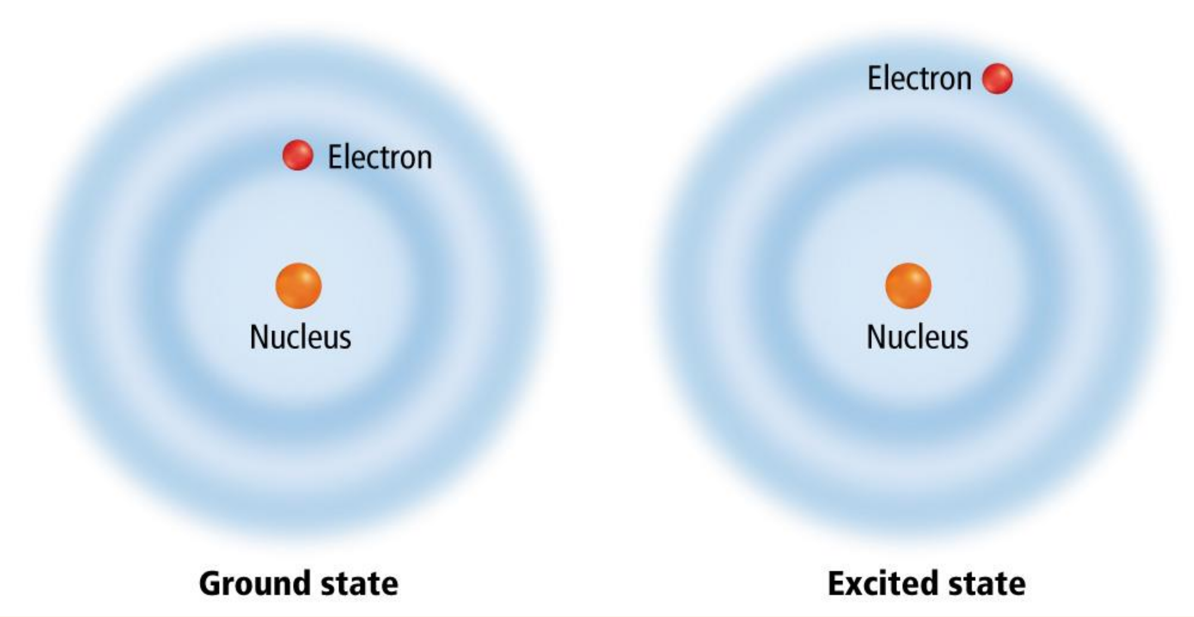
- Einstein's theory of light's dual nature accounted for several unexplainable phenomena but not why atomic emission spectra of elements were discontinuous rather continuous.
- In 1913, Niels Bohr, a Danish physicist working in Rutherford's laboratory, proposed a quantum model for the hydrogen atom that seemed to answer this question.

Bohr's Model of the Atom (cont.)

- Bohr correctly predicted the frequency lines in hydrogen’s atomic emission spectrum.
- The lowest allowable energy state of an atom is called its **ground state**.
- When an atom gains energy, it is in an excited state.

Bohr's Model of the Atom (cont.)

- Bohr suggested that an electron moves around the nucleus only in certain allowed circular orbits.



Bohr's Model of the Atom (cont.)

- Each orbit was given a number, called the **quantum number**.

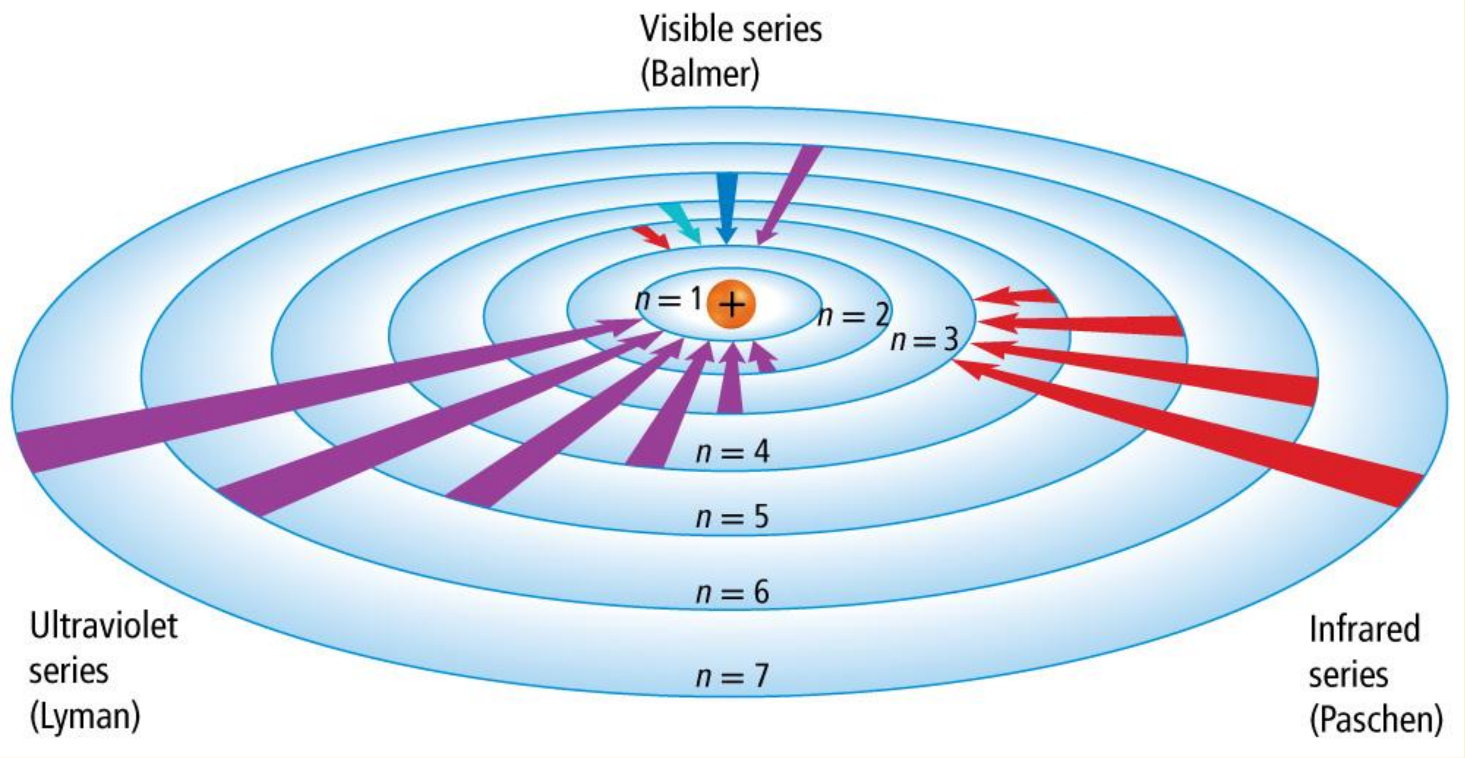
Table 5.1 Bohr's Description of the Hydrogen Atom

Bohr's Atomic Orbit	Quantum Number	Orbit Radius (nm)	Corresponding Atomic Energy Level	Relative Energy
First	$n = 1$	0.0529	1	E_1
Second	$n = 2$	0.212	2	$E_2 = 4E_1$
Third	$n = 3$	0.476	3	$E_3 = 9E_1$
Fourth	$n = 4$	0.846	4	$E_4 = 16E_1$
Fifth	$n = 5$	1.32	5	$E_5 = 25E_1$
Sixth	$n = 6$	1.90	6	$E_6 = 36E_1$
Seventh	$n = 7$	2.59	7	$E_7 = 49E_1$

Bohr's Model of the Atom (cont.)

- Hydrogen’s single electron is in the n = 1 orbit in the ground state.
- When energy is added, the electron moves to the n = 2 orbit.

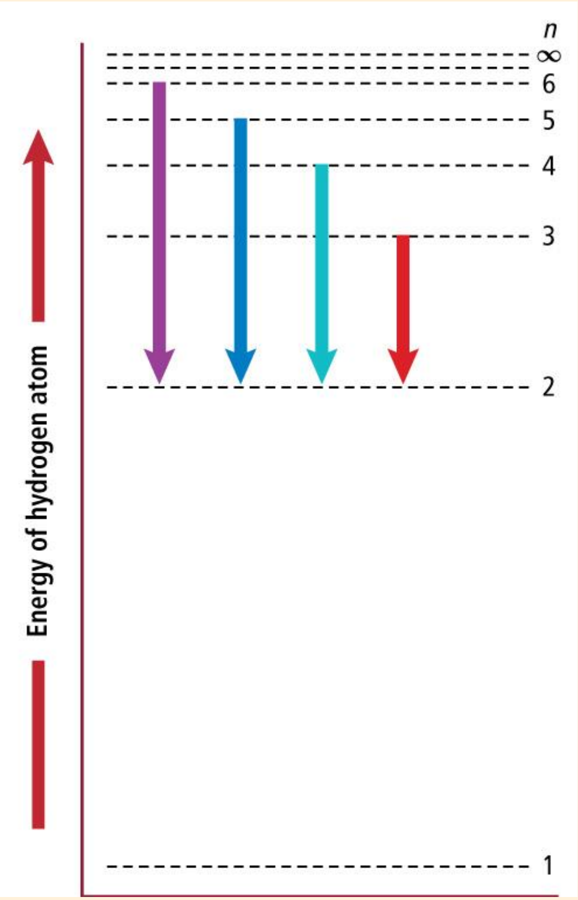
Bohr's Model of the Atom (cont.)



Concepts In Motion

Bohr's Model of the Atom (cont.)

Concepts In Motion



Bohr's Model of the Atom (cont.)

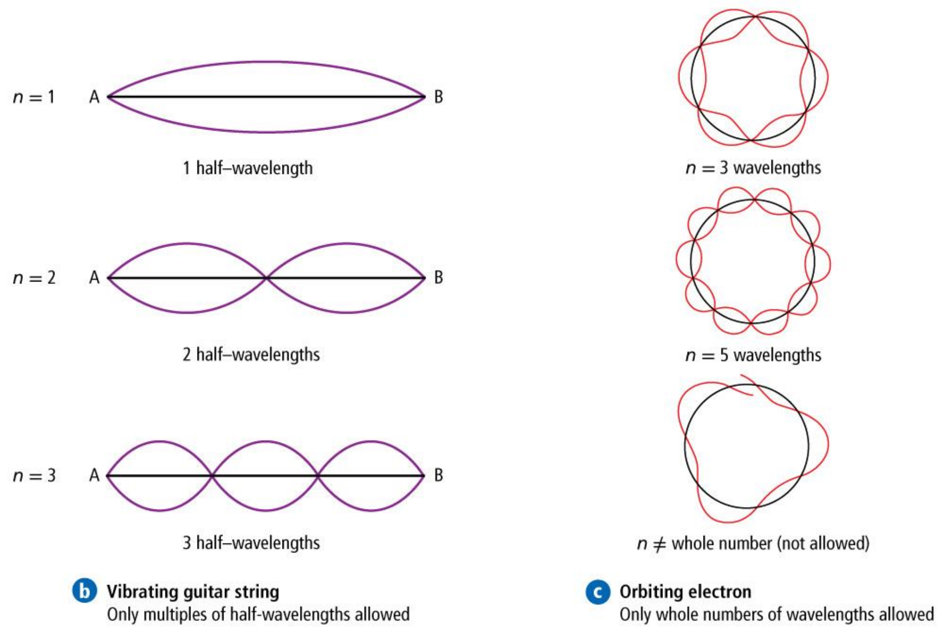
- Bohr’s model explained the hydrogen’s spectral lines, but failed to explain any other element’s lines.
- The behavior of electrons is still not fully understood, but it is known they do not move around the nucleus in circular orbits.

The Quantum Mechanical Model of the Atom

- Louis de Broglie (1892–1987) hypothesized that particles, including electrons, could also have wavelike behaviors.

The Quantum Mechanical Model of the Atom (cont.)

- The figure illustrates that electrons orbit the nucleus only in whole-number wavelengths.



The Quantum Mechanical Model of the Atom (cont.)

- The **de Broglie equation** predicts that all moving particles have wave characteristics.

Particle Electromagnetic–Wave Relationship

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

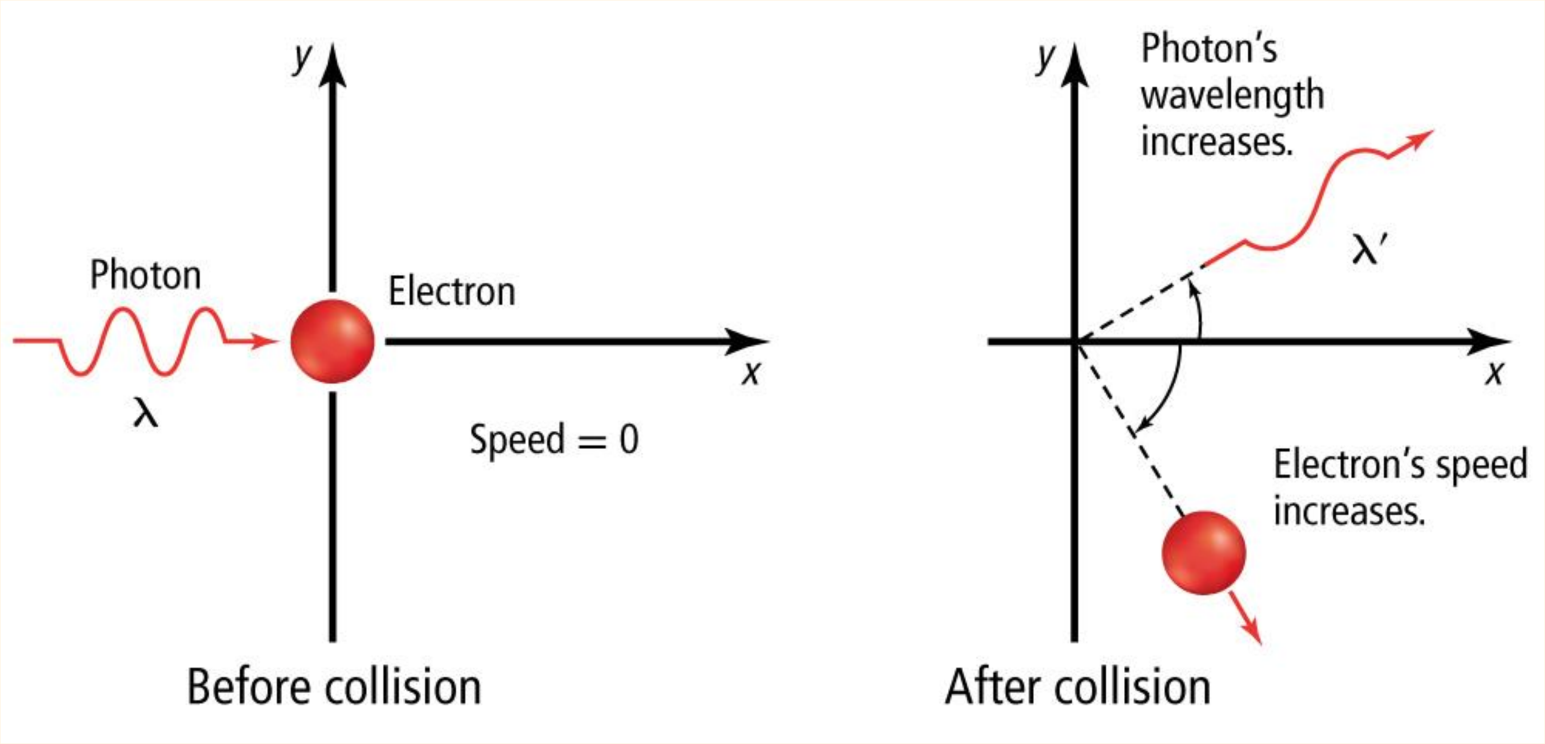
λ represents wavelength.
h is Planck's constant.
m represents mass of the particle.
v represents velocity.

The wavelength of a particle is the ratio of Planck's constant and the product of the particle's mass and its velocity.

The Quantum Mechanical Model of the Atom (cont.)

- Heisenberg showed it is impossible to take any measurement of an object without disturbing it.
- The **Heisenberg uncertainty principle** states that it is fundamentally impossible to know precisely both the velocity and position of a particle at the same time.
- The only quantity that can be known is the probability for an electron to occupy a certain region around the nucleus.

The Quantum Mechanical Model of the Atom (cont.)

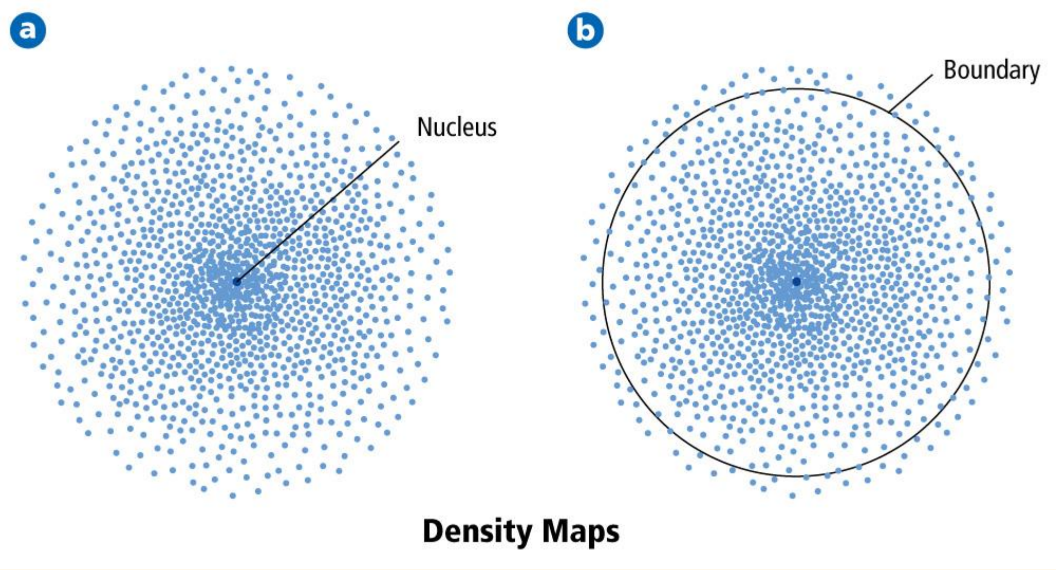


The Quantum Mechanical Model of the Atom (cont.)

- Schrödinger treated electrons as waves in a model called the **quantum mechanical model of the atom**.
- Schrödinger's equation applied equally well to elements other than hydrogen.

The Quantum Mechanical Model of the Atom (cont.)

- The wave function predicts a three-dimensional region around the nucleus called the **atomic orbital**.

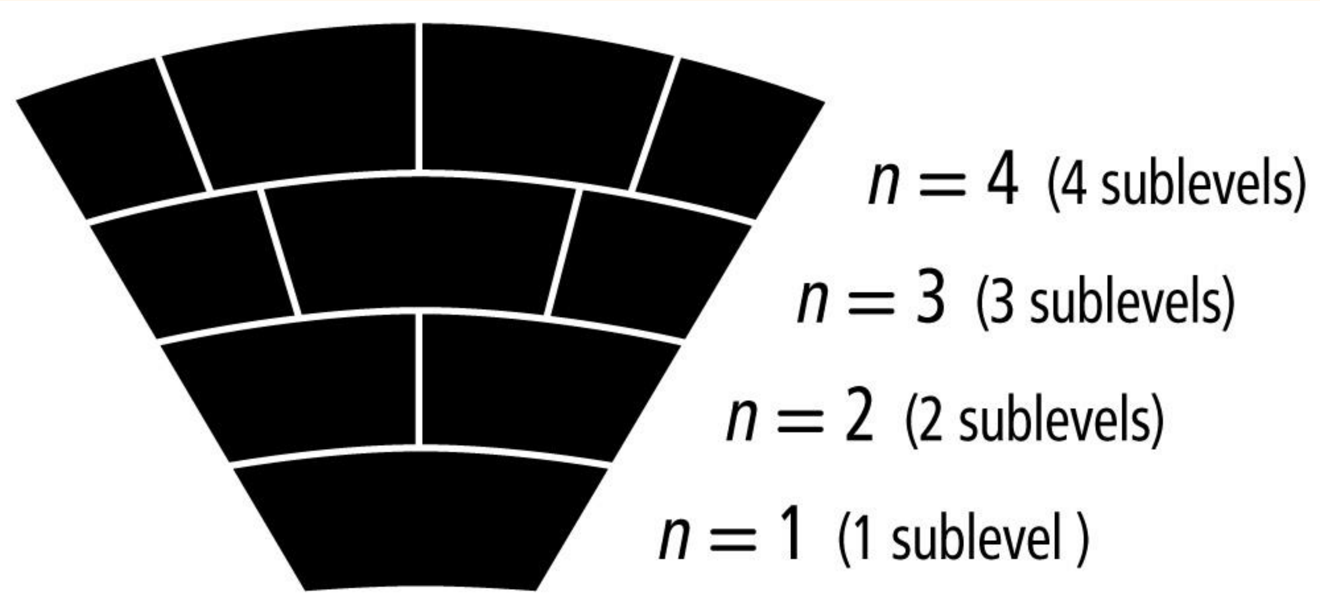


Hydrogen Atomic Orbitals

- **Principal quantum number** (*n*) indicates the relative size and energy of atomic orbitals.
- *n* specifies the atom's major energy levels, called the **principal energy levels**.

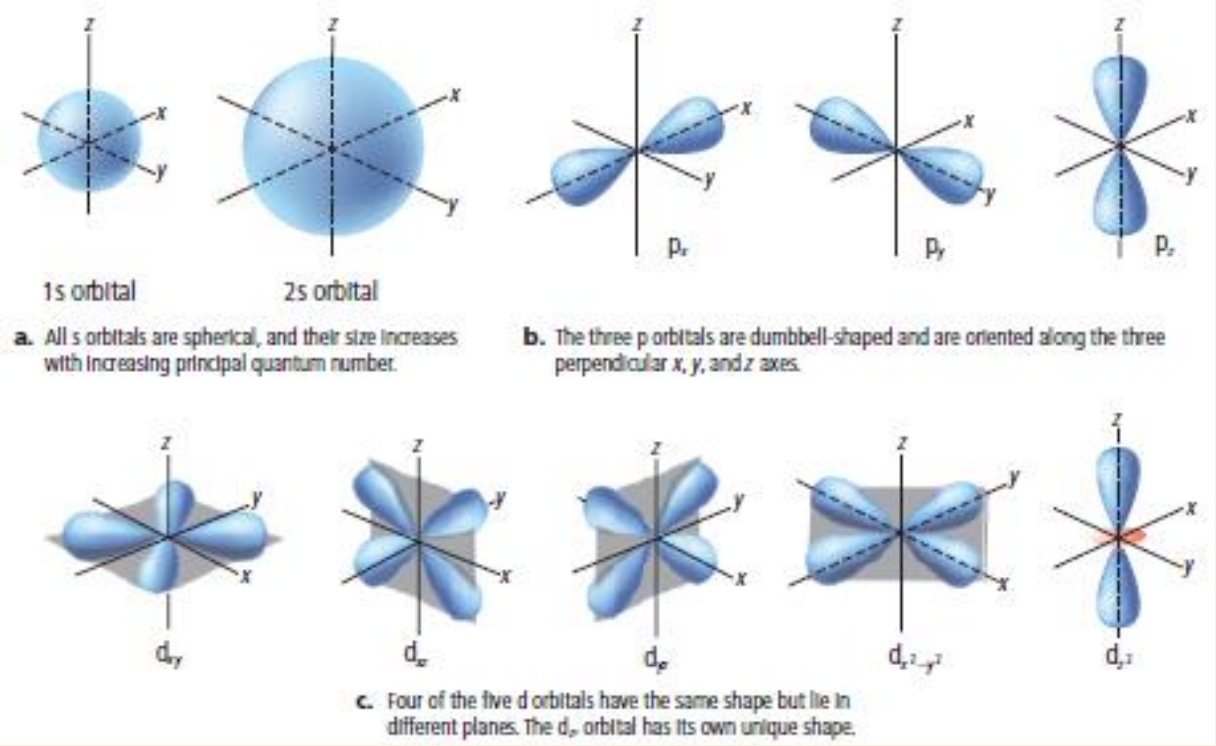
Hydrogen Atomic Orbitals (cont.)

- **Energy sublevels** are contained within the principal energy levels.



Hydrogen Atomic Orbitals (cont.)

- Each energy sublevel relates to orbitals of different shape.



Hydrogen Atomic Orbitals (cont.)

Table 5.2 Hydrogen's First Four Principal Energy Levels

Principal Quantum Number (n)	Sublevels (Types of Orbitals) Present	Number of Orbitals Related to Sublevel	Total Number of Orbitals Related to Principal Energy Level (n^2)
1	s	1	1
2	s p	1 3	4
3	s p d	1 3 5	9
4	s p d f	1 3 5 7	16

Section Check

Which atomic suborbitals have a "dumbbell" shape?

A. s

B. f

C. p

D. d

Section Check

Who proposed that particles could also exhibit wavelike behaviors?

A. Bohr

B. Einstein

C. Rutherford

D. de Broglie

Click here to go back to the chapter menu.

Electron Configuration

Objectives

- **Apply** the Pauli exclusion principle, the aufbau principle, and Hund's rule to write electron configurations using orbital diagrams and electron configuration notation.
- **Define** valence electrons, and draw electron-dot structures representing an atom's valence electrons.

Review Vocabulary

electron: a negatively charged, fast-moving particle with an extremely small mass that is found in all forms of matter and moves through the empty space surrounding an atom's nucleus

New Vocabulary

electron configuration

aufbau principle

Pauli exclusion principle

Hund's rule

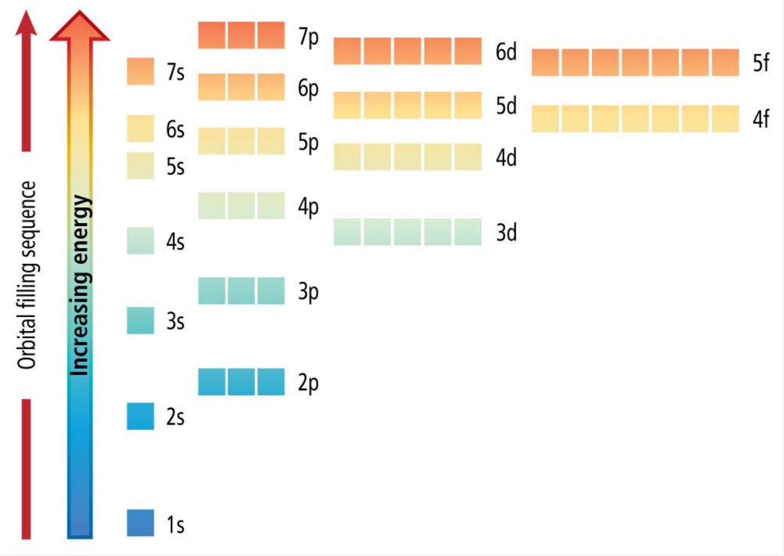
valence electrons

electron-dot structure

MAIN Idea **A set of three rules determines the arrangement in an atom.**

Ground-State Electron Configuration

- The arrangement of electrons in the atom is called the **electron configuration**.
- The **aufbau principle** states that each electron occupies the lowest energy orbital available.



Ground-State Electron Configuration (cont.)

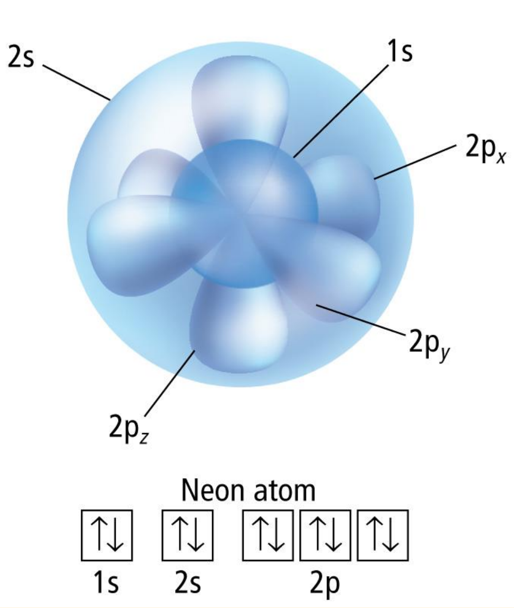
Table 5.3 Features of the Aufbau Diagram

Feature	Example
All orbitals related to an energy sublevel are of equal energy.	All three 2p orbitals are of equal energy.
In a multi-electron atom, the energy sublevels within a principal energy level have different energies.	The three 2p orbitals are of higher energy than the 2s orbital.
In order of increasing energy, the sequence of energy sublevels within a principal energy level is s, p, d, and f.	If $n = 4$, then the sequence of energy sublevels is 4s, 4p, 4d, and 4f.
Orbitals related to energy sublevels within one principal energy level can overlap orbitals related to energy sublevels within another principal level.	The orbital related to the atom's 4s sublevel has a lower energy than the five orbitals related to the 3d sublevel.

Electron Configuration

Ground-State Electron Configuration (cont.)

- The **Pauli exclusion principle** states that a maximum of two electrons can occupy a single orbital, but only if the electrons have opposite spins.
- **Hund's rule** states that single electrons with the same spin must occupy each equal-energy orbital before additional electrons with opposite spins can occupy the same energy level orbitals.



Ground-State Electron Configuration (cont.)

Concepts In Motion

Table 5.4 Electron Configurations and Orbital Diagrams for Elements 1–10

Element	Atomic Number	Orbital Diagram 1s 2s $2p_x$ $2p_y$ $2p_z$	Electron Configuration Notation
Hydrogen	1	↑	$1s^1$
Helium	2	↑↓	$1s^2$
Lithium	3	↑↓ ↑	$1s^2\ 2s^1$
Beryllium	4	↑↓ ↑↓	$1s^2\ 2s^2$
Boron	5	↑↓ ↑↓ ↑	$1s^2\ 2s^2\ 2p^1$
Carbon	6	↑↓ ↑↓ ↑ ↑	$1s^2\ 2s^2\ 2p^2$
Nitrogen	7	↑↓ ↑↓ ↑ ↑ ↑	$1s^2\ 2s^2\ 2p^3$
Oxygen	8	↑↓ ↑↓ ↑↓ ↑ ↑	$1s^2\ 2s^2\ 2p^4$
Fluorine	9	↑↓ ↑↓ ↑↓ ↑↓ ↑	$1s^2\ 2s^2\ 2p^5$
Neon	10	↑↓ ↑↓ ↑↓ ↑↓ ↑↓	$1s^2\ 2s^2\ 2p^6$

Ground-State Electron Configuration (cont.)

- Noble gas notation uses noble gas symbols in brackets to shorten inner electron configurations of other elements.

Table 5.5 Electron Configurations for Elements 11–18

Element	Atomic Number	Complete Electron Configuration	Electron Configuration Using Noble Gas
Sodium	11	$1s^22s^22p^63s^1$	$[Ne]3s^1$
Magnesium	12	$1s^22s^22p^63s^2$	$[Ne]3s^2$
Aluminum	13	$1s^22s^22p^63s^23p^1$	$[Ne]3s^23p^1$
Silicon	14	$1s^22s^22p^63s^23p^2$	$[Ne]3s^23p^2$
Phosphorus	15	$1s^22s^22p^63s^23p^3$	$[Ne]3s^23p^3$
Sulfur	16	$1s^22s^22p^63s^23p^4$	$[Ne]3s^23p^4$
Chlorine	17	$1s^22s^22p^63s^23p^5$	$[Ne]3s^23p^5$
Argon	18	$1s^22s^22p^63s^23p^6$	$[Ne]3s^23p^6$ or [Ar]

Ground-State Electron Configuration (cont.)

- The aufbau diagram can be used to write correct ground-state electron configurations for all elements up to and including Vanadium, atomic number 23.
- The electron configurations for certain transition metals, like chromium and copper, do not follow the aufbau diagram due to increased stability of half-filled and filled sets of s and d orbitals.

Valence Electrons

- **Valence electrons** are defined as electrons in the atom's outermost orbitals—those associated with the atom's highest principal energy level.
- **Electron-dot structure** consists of the element's symbol representing the nucleus, surrounded by dots representing the element's valence electrons.

Valence Electrons (cont.)

Concepts In Motion

Table 5.6 Electron Configurations and Dot Structures

Element	Atomic Number	Electron Configuration	Electron-Dot Structure
Lithium	3	$1s^2 2s^1$	Li·
Beryllium	4	$1s^2 2s^2$	·Be·
Boron	5	$1s^2 2s^2 2p^1$	·Ḃ·
Carbon	6	$1s^2 2s^2 2p^2$	·Ċ· (with one dot below)
Nitrogen	7	$1s^2 2s^2 2p^3$	·N̈· (with one dot below)
Oxygen	8	$1s^2 2s^2 2p^4$	:Ö· (with one dot below)
Fluorine	9	$1s^2 2s^2 2p^5$	:F̈· (with two dots below)
Neon	10	$1s^2 2s^2 2p^6$	:N̈e: (with two dots below)

Section Check

In the ground state, which orbital does an atom's electrons occupy?

A. the highest available

B. the lowest available

C. the n = 0 orbital

D. the d suborbital

Section Check

The outermost electrons of an atom are called what?

A. suborbitals

B. orbitals

C. ground state electrons

D. valence electrons

Click here to go back to the chapter menu.

McGraw Hill Education

Resources

Chemistry Online

Study Guide

Chapter Assessment

Standardized Test Practice

Study Guide

Key Concepts

- All waves are defined by their wavelengths, frequencies, amplitudes, and speeds.
  $c = \lambda \nu$
- In a vacuum, all electromagnetic waves travel at the speed of light.
- All electromagnetic waves have both wave and particle properties.
- Matter emits and absorbs energy in quanta.
  $E_{quantum} = h\nu$

Study Guide

Key Concepts

- White light produces a continuous spectrum. An element's emission spectrum consists of a series of lines of individual colors.

Study Guide

Key Concepts

- Bohr's atomic model attributes hydrogen's emission spectrum to electrons dropping from higher-energy to lower-energy orbits.

  $$\Delta E = E_{\text{higher-energy orbit}} - E_{\text{lower-energy orbit}} = E_{\text{photon}} = h\nu$$

- The de Broglie equation relates a particle's wavelength to its mass, its velocity, and Planck's constant.

  $\lambda = h / m\nu$

- The quantum mechanical model of the atom assumes that electrons have wave properties.

- Electrons occupy three-dimensional regions of space called atomic orbitals.

Study Guide

Key Concepts

- The arrangement of electrons in an atom is called the atom’s electron configuration.
- Electron configurations are defined by the aufbau principle, the Pauli exclusion principle, and Hund’s rule.
- An element’s valence electrons determine the chemical properties of the element.
- Electron configurations can be represented using orbital diagrams, electron configuration notation, and electron-dot structures.

Chapter Assessment

The shortest distance from equivalent points on a continuous wave is the:

A. frequency

B. wavelength

C. amplitude

D. crest

Chapter Assessment

The energy of a wave increases as ____.

A. frequency decreases

B. wavelength decreases

C. wavelength increases

D. distance increases

Chapter Assessment

Atom's move in circular orbits in which atomic model?

A. quantum mechanical model

B. Rutherford's model

C. Bohr's model

D. plum-pudding model

Chapter Assessment

It is impossible to know precisely both the location and velocity of an electron at the same time because:

A. the Pauli exclusion principle

B. the dual nature of light

C. electrons travel in waves

D. the Heisenberg uncertainty principle

Chapter Assessment

How many valence electrons does neon have?

A. 0

B. 1

C. 7

D. 8

Standardized Test Practice

Spherical orbitals belong to which sublevel?

A. s

B. p

C. d

D. f

Standardized Test Practice

What is the maximum number of electrons the 1s orbital can hold?

A. 10

B. 2

C. 8

D. 1

Standardized Test Practice

In order for two electrons to occupy the same orbital, they must:

A. have opposite charges

B. have opposite spins

C. have the same spin

D. have the same spin and charge

Standardized Test Practice

How many valence electrons does boron contain?

A. 1

B. 2

C. 3

D. 5

Standardized Test Practice

What is a quantum?

A. another name for an atom

B. the smallest amount of energy that can be gained or lost by an atom

C. the ground state of an atom

D. the excited state of an atom