Section Summary

30.1 Discovery of the Atom

- Atoms are the smallest unit of elements; atoms combine to form molecules, the smallest unit of compounds.
- The first direct observation of atoms was in Brownian motion.
- Analysis of Brownian motion gave accurate sizes for atoms (10^{-10} m on average) and a precise value for Avogadro's number.

30.2 Discovery of the Parts of the Atom: Electrons and Nuclei

- Atoms are composed of negatively charged electrons, first proved to exist in cathode-ray-tube experiments, and a positively charged nucleus.
- All electrons are identical and have a charge-to-mass ratio of

$$\frac{q_e}{m_e} = -1.76\times10^{11}\text{ C/kg.}$$

- The positive charge in the nuclei is carried by particles called protons, which have a charge-to-mass ratio of

$$\frac{q_p}{m_p} = 9.57\times10^{7}\text{ C/kg.}$$

- Mass of electron,

$$m_e = 9.11\times10^{-31}\text{ kg.}$$

- Mass of proton,

$$m_p = 1.67\times10^{-27}\text{ kg.}$$

- The planetary model of the atom pictures electrons orbiting the nucleus in the same way that planets orbit the sun.

30.3 Bohr's Theory of the Hydrogen Atom

- The planetary model of the atom pictures electrons orbiting the nucleus in the way that planets orbit the sun. Bohr used the planetary model to develop the first reasonable theory of hydrogen, the simplest atom. Atomic and molecular spectra are quantized, with hydrogen spectrum wavelengths given by the formula

$$\frac{1}{\lambda} = R\left(\frac{1}{n_\mathrm{f}^2} - \frac{1}{n_\mathrm{i}^2}\right),$$

where λ is the wavelength of the emitted EM radiation and R is the Rydberg constant, which has the value

$$R = 1.097\times10^7\ \mathrm{m}^{-1}.$$

- The constants n_i and n_f are positive integers, and n_i must be greater than n_f .
- Bohr correctly proposed that the energy and radii of the orbits of electrons in atoms are quantized, with energy for transitions between orbits given by

$$\Delta E = hf = E_\mathrm{i} - E_\mathrm{f},$$

where ΔE is the change in energy between the initial and final orbits and hf is the energy of an absorbed or emitted photon. It is useful to plot orbital energies on a vertical graph called an energy-level diagram.

- Bohr proposed that the allowed orbits are circular and must have quantized orbital angular momentum given by

$$L = m_e v r_n = n\frac{h}{2\pi}(n = 1, 2, 3\ \ldots),$$

where L is the angular momentum, r_n is the radius of the nth orbit, and h is Planck's constant. For all one-electron (hydrogen-like) atoms, the radius of an orbit is given by

$$r_n = \frac{n^2}{Z}a_\mathrm{B}(\text{allowed orbits } n = 1, 2, 3, ...),$$

Z is the atomic number of an element (the number of electrons is has when neutral) and a_B is defined to be the Bohr radius, which is

$$a_\mathrm{B} = \frac{h^2}{4\pi^2 m_e k q_e^2} = 0.529\times10^{-10}\ \mathrm{m}.$$

- Furthermore, the energies of hydrogen-like atoms are given by

$$E_n = -\frac{Z^2}{n^2}E_0(n = 1, 2, 3\ ...),$$

where E_0 is the ground-state energy and is given by

$$E_0 = \frac{2\pi^2 q_e^4 m_e k^2}{h^2} = 13.6\ \mathrm{eV}.$$

Thus, for hydrogen,

$$E_n = -\frac{13.6\ \mathrm{eV}}{n^2}(n,\ =,\ 1, 2, 3\ ...).$$

- The Bohr Theory gives accurate values for the energy levels in hydrogen-like atoms, but it has been improved upon in several respects.

30.4 X Rays: Atomic Origins and Applications

- X rays are relatively high-frequency EM radiation. They are produced by transitions between inner-shell electron levels, which produce x rays characteristic of the atomic element, or by accelerating electrons.
- X rays have many uses, including medical diagnostics and x-ray diffraction.

30.5 Applications of Atomic Excitations and De-Excitations

- An important atomic process is fluorescence, defined to be any process in which an atom or molecule is excited by absorbing a photon of a given energy and de-excited by emitting a photon of a lower energy.
- Some states live much longer than others and are termed metastable.
- Phosphorescence is the de-excitation of a metastable state.
- Lasers produce coherent single-wavelength EM radiation by stimulated emission, in which a metastable state is stimulated to decay.
- Lasing requires a population inversion, in which a majority of the atoms or molecules are in their metastable state.

30.6 The Wave Nature of Matter Causes Quantization

- Quantization of orbital energy is caused by the wave nature of matter. Allowed orbits in atoms occur for constructive interference of electrons in the orbit, requiring an integral number of wavelengths to fit in an orbit's circumference; that is,

$$n\lambda_n = 2\pi r_n(n = 1, 2, 3\ ...),$$

where λ_n is the electron's de Broglie wavelength.

- Owing to the wave nature of electrons and the Heisenberg uncertainty principle, there are no well-defined orbits; rather, there are clouds of probability.
- Bohr correctly proposed that the energy and radii of the orbits of electrons in atoms are quantized, with energy for transitions between orbits given by

$$\Delta E = hf = E_\mathrm{i} - E_\mathrm{f},$$

where ΔE is the change in energy between the initial and final orbits and hf is the energy of an absorbed or emitted photon.
- It is useful to plot orbit energies on a vertical graph called an energy-level diagram.
- The allowed orbits are circular, Bohr proposed, and must have quantized orbital angular momentum given by

$$L = m_e v r_n = n\frac{h}{2\pi}(n = 1, 2, 3 \ldots),$$

where L is the angular momentum, r_n is the radius of orbit n , and h is Planck's constant.

30.7 Patterns in Spectra Reveal More Quantization

- The Zeeman effect—the splitting of lines when a magnetic field is applied—is caused by other quantized entities in atoms.
- Both the magnitude and direction of orbital angular momentum are quantized.
- The same is true for the magnitude and direction of the intrinsic spin of electrons.

30.8 Quantum Numbers and Rules

- Quantum numbers are used to express the allowed values of quantized entities. The principal quantum number n labels the basic states of a system and is given by

$$n = 1, 2, 3, \ldots.$$

- The magnitude of angular momentum is given by

$$L = \sqrt{l(l+1)}\frac{h}{2\pi} \quad (l = 0, 1, 2, \ldots, n-1),$$

where l is the angular momentum quantum number. The direction of angular momentum is quantized, in that its component along an axis defined by a magnetic field, called the z -axis is given by

$$L_z = m_l\frac{h}{2\pi} \quad (m_l = -l, -l+1, \ldots, -1, 0, 1, \ldots l-1, l),$$

where L_z is the z -component of the angular momentum and m_l is the angular momentum projection quantum number. Similarly, the electron's intrinsic spin angular momentum S is given by

$$S = \sqrt{s(s+1)}\frac{h}{2\pi} \quad (s = 1/2 \text{ for electrons}),$$

s is defined to be the spin quantum number. Finally, the direction of the electron's spin along the z -axis is given by

$$S_z = m_s\frac{h}{2\pi} \quad \left(m_s = -\frac{1}{2}, +\frac{1}{2}\right),$$

where S_z is the z -component of spin angular momentum and m_s is the spin projection quantum number. Spin projection $m_s = +1/2$ is referred to as spin up, whereas $m_s = -1/2$ is called spin down. Table 30.1 summarizes the atomic quantum numbers and their allowed values.

30.9 The Pauli Exclusion Principle

- The state of a system is completely described by a complete set of quantum numbers. This set is written as (n, l, m_l, m_s).
- The Pauli exclusion principle says that no two electrons can have the same set of quantum numbers; that is, no two electrons can be in the same state.
- This exclusion limits the number of electrons in atomic shells and subshells. Each value of n corresponds to a shell, and each value of l corresponds to a subshell.
- The maximum number of electrons that can be in a subshell is $2(2l+1)$.
- The maximum number of electrons that can be in a shell is $2n^2$.

tunneling: a quantum mechanical process of potential energy barrier penetration

Section Summary

31.1 Nuclear Radioactivity

- Some nuclei are radioactive—they spontaneously decay destroying some part of their mass and emitting energetic rays, a process called nuclear radioactivity.
- Nuclear radiation, like x rays, is ionizing radiation, because energy sufficient to ionize matter is emitted in each decay.
- The range (or distance traveled in a material) of ionizing radiation is directly related to the charge of the emitted particle and its energy, with greater-charge and lower-energy particles having the shortest ranges.
- Radiation detectors are based directly or indirectly upon the ionization created by radiation, as are the effects of radiation on living and inert materials.

31.2 Radiation Detection and Detectors

- Radiation detectors are based directly or indirectly upon the ionization created by radiation, as are the effects of radiation on living and inert materials.

31.3 Substructure of the Nucleus

- Two particles, both called nucleons, are found inside nuclei. The two types of nucleons are protons and neutrons; they are very similar, except that the proton is positively charged while the neutron is neutral. Some of their characteristics are given in **Table 31.2** and compared with those of the electron. A mass unit convenient to atomic and nuclear processes is the unified atomic mass unit (u), defined to be

$$1\text{ u} = 1.6605\times10^{-27}\text{ kg} = 931.46\text{ MeV}/c^2.$$

- A nuclide is a specific combination of protons and neutrons, denoted by

$$^{A}_{Z}\text{X}_N \text{ or simply } ^{A}\text{X},$$

Z is the number of protons or atomic number, X is the symbol for the element, N is the number of neutrons, and A is the mass number or the total number of protons and neutrons,

$$A = N + Z.$$

- Nuclides having the same Z but different N are isotopes of the same element.
- The radius of a nucleus, r, is approximately

$$r = r_0 A^{1/3},$$

where $r_0 = 1.2\text{ fm}$. Nuclear volumes are proportional to A. There are two nuclear forces, the weak and the strong. Systematics in nuclear stability seen on the chart of the nuclides indicate that there are shell closures in nuclei for values of Z and N equal to the magic numbers, which correspond to highly stable nuclei.

31.4 Nuclear Decay and Conservation Laws

- When a parent nucleus decays, it produces a daughter nucleus following rules and conservation laws. There are three major types of nuclear decay, called alpha (α), beta (β), and gamma (γ). The α decay equation is

$$^{A}_{Z}\text{X}_N \rightarrow {}^{A-4}_{Z-2}\text{Y}_{N-2} + {}^{4}_{2}\text{He}_2.$$

- Nuclear decay releases an amount of energy E related to the mass destroyed Δm by

$$E = (\Delta m)c^2.$$

- There are three forms of beta decay. The β^- decay equation is

$$^{A}_{Z}\text{X}_N \rightarrow {}^{A}_{Z+1}\text{Y}_{N-1} + \beta^- + \bar{\nu}_e.$$

- The β^+ decay equation is

$$^{A}_{Z}\text{X}_N \rightarrow {}^{A}_{Z-1}\text{Y}_{N+1} + \beta^+ + \nu_e.$$

- The electron capture equation is

$$^{A}_{Z}\text{X}_N + e^- \rightarrow {}^{A}_{Z-1}\text{Y}_{N+1} + \nu_e.$$

- β^- is an electron, β^+ is an antielectron or positron, ν_e represents an electron's neutrino, and $\bar{\nu}_e$ is an electron's antineutrino. In addition to all previously known conservation laws, two new ones arise— conservation of electron family number and conservation of the total number of nucleons. The γ decay equation is

$$X_N^* \rightarrow X_N + \gamma_1 + \gamma_2 + \cdots$$

γ is a high-energy photon originating in a nucleus.

31.5 Half-Life and Activity

- Half-life $t_{1/2}$ is the time in which there is a 50% chance that a nucleus will decay. The number of nuclei N as a function of time is

$$N = N_0 e^{-\lambda t},$$

where N_0 is the number present at $t = 0$, and λ is the decay constant, related to the half-life by

$$\lambda = \frac{0.693}{t_{1/2}}.$$

- One of the applications of radioactive decay is radioactive dating, in which the age of a material is determined by the amount of radioactive decay that occurs. The rate of decay is called the activity R:

$$R = \frac{\Delta N}{\Delta t}.$$

- The SI unit for R is the becquerel (Bq), defined by

$$1 \text{ Bq} = 1 \text{ decay/s}.$$

- R is also expressed in terms of curies (Ci), where

$$1 \text{ Ci} = 3.70 \times 10^{10} \text{ Bq}.$$

- The activity R of a source is related to N and $t_{1/2}$ by

$$R = \frac{0.693 N}{t_{1/2}}.$$

- Since N has an exponential behavior as in the equation $N = N_0 e^{-\lambda t}$, the activity also has an exponential behavior, given by

$$R = R_0 e^{-\lambda t},$$

where R_0 is the activity at $t = 0$.

31.6 Binding Energy

- The binding energy (BE) of a nucleus is the energy needed to separate it into individual protons and neutrons. In terms of atomic masses,

$$\text{BE} = \{[Zm(^1\text{H}) + Nm_n] - m(^A\text{X})\}c^2,$$

where $m\left(^1\text{H}\right)$ is the mass of a hydrogen atom, $m\left(^A\text{X}\right)$ is the atomic mass of the nuclide, and m_n is the mass of a neutron. Patterns in the binding energy per nucleon, BE/A, reveal details of the nuclear force. The larger the BE/A, the more stable the nucleus.

31.7 Tunneling

- Tunneling is a quantum mechanical process of potential energy barrier penetration. The concept was first applied to explain α decay, but tunneling is found to occur in other quantum mechanical systems.