Chapter 2: The Nature of Molecules and the Properties of Water

Biology is the study of living things, and it is important to understand their chemical nature. The processes that allow life to exist follow chemical rules. All matter is made of atoms, which interact with each other in order for chemical reactions to occur in biological systems.

TAKE NOTE: *While the AP Biology Exam does not test this material directly, it is important to have a solid understanding of the concepts in this chapter in order to properly understand the biochemistry that is to follow. It is important to have a working knowledge of the elements that are important for life, the role of isotopes in biology, and the different types of bonds that form between elements. The properties of water are extremely important, as well as the behavior of acids and bases.*

2.1 The Nature of Atoms

An atom contains a nucleus and orbiting, negatively-charged **electrons**. The nucleus has two subatomic particles: **neutrons**, which have no charge and **protons**, which are positively charged. An element is the smallest unit that retains the chemical properties of an atom.

An atom's **atomic number** is equal to the number of protons and its **atomic mass** equals the masses of protons and neutrons. Atomic mass is measured in daltons; the mass of a proton is about one dalton, as is the mass of a neutron. A **mole** of a substance is the weight in grams equal to the atomic masses of all of the atoms in that substance. One mole has 6.02×10^{23} atoms or molecules of the particular material.

Electrons are found in **orbitals** around the nucleus. The number of electrons usually equals the number of protons. When these numbers are unequal, the atom is charged and is called an **ion**. A positively charged atom has more protons than electrons and is called a **cation**; a negatively charged atom has more electron than protons and is called an **anion**.

The **isotopes** of an element have differing numbers of neutrons. This does not change the atomic number but does change the atomic mass. Some isotopes are **radioactive** and emit energy during the breakup of the nucleus.

Electrons determine the chemistry of atoms. The electrons are found at discrete energy levels and have potential energy. The farther away an electron is from the nucleus, the greater potential energy it has. Energy is released when an electron moves to a lower level and energy is absorbed when it moves to a higher level.

Electrons can move between atoms during chemical reactions called **oxidation-reduction** (redox) reactions; this allows for energy to be transferred between atoms. Oxidation occurs when an electron is lost and reduction is when an electron is gained.

2.2 Elements Found in Living Systems

Valence electrons, the electrons in the outer most energy level, can participate in chemical bonds. Most atoms in living systems follow the octet rule and react with other atoms to have eight associated electrons.

The common elements in living systems are C, H, O, N, P, S, N, Na, K, Ca, Mg, Fe, and Cl. Other elements are found in trace amounts.

2.3 The Nature of Chemical Bonds

Molecules contain multiple atoms held together by chemical bonds. Anions and cations can associate by giving or receiving electrons, forming ionic bonds. Covalent bonds form between atoms when electrons are shared. A single covalent bond has one pair of electrons. Carbon atoms, which have four valence electrons, can form four covalent bonds. In nonpolar bonds, the electrons are shared equally between the atoms. However, in some cases, the sharing of electrons is unequal. This is because some atoms are more electronegative, meaning that they have a higher affinity for electrons. The electrons spend more time around the more electronegative atom, making that atom partially negative, and forming a polar covalent bond.

A hydrogen bond is a weak interaction between a strongly electronegative atom and a hydrogen atom on another molecule. They are important in stabilizing the structure of many biological molecules.

Chemical reactions occur when chemical bonds are rearranged. They begin with reactants and result in products.

TAKE NOTE: *You should know the different types of chemical bonds and how electrons are involved in each.*

2.4 Water: A Vital Compound

Water is a compound of two hydrogen atoms and one oxygen atom with a polar covalent bond between the oxygen and each hydrogen. Water molecules are attracted to each other when the partially positive hydrogen atom of one water molecule is attracted to the partially negative oxygen atom in an adjacent water molecule. This association is called a hydrogen bond. Hydrogen bonding is responsible for the chemistry of water. Because of hydrogen bonding, water molecules are cohesive, meaning they are attracted to each other. This cohesion creates surface tension, which allows objects to float on water. Water can also form hydrogen bonds with other polar molecules; this is called adhesion.

2.5 Properties of Water

Water has a high specific heat. This means that it takes a large amount of energy to break the hydrogen bonds between water molecules. This property allows water to insulate against wide temperature swings

because it changes its temperature slowly. Water also has a high heat of vaporization; it absorbs much energy in changing from a liquid into a gas. This allows organisms to lose excess body heat by evaporative cooling.

The hydrogen bond arrangement between water molecules makes solid water (ice) less dense that liquid water because the water molecules are spaced widely apart. This is important because it causes large bodies of water to freeze from the top, allowing the ice to insulate the organisms that live below the surface of the water during the winter.

Water molecules dissolve other substances by surrounding them in a hydration shell. Water is a good solvent of polar molecules or solutes. Polar molecules form hydrogen bonds with water and are hydrophilic. Water does not form many hydrogen bonds with nonpolar substances; these are hydrophobic molecules. Hydrophobic molecules aggregate to limit their interactions with water. This is important in the shape and formation of cellular membranes, proteins, and DNA.

Water ionizes into an anion (hydroxide ion; OH^-) and a cation (proton or hydrogen ion; H^+). In pure water the molar concentration of H^+ is 10^{-7} moles/liter.

TAKE NOTE: *Water is necessary for life; therefore, you should understand the importance of its polar covalent bonds, the ability of hydrogen to bond to other molecules, and its role in the arrangement of other molecules through hydrophilic and hydrophobic interactions.*

2.6 Acids and Bases

The pH equals –log [H^+]. The pH scale ranges from 0 to 14. Acids release H^+ and have a pH less than 7. Pure water has a pH of 7 and is neutral. Bases accept H^+ and have pHs greater than 7. Buffers either release or bind protons, thereby reducing pH change. The carbonic acid (carbonate)-biocarbonate buffering system helps maintain the pH in the blood and tissues. This is an important aspect of homeostasis in the body.

TAKE NOTE: *Review the carbonic acid-bicarbonate buffer system and how carbon dioxide is involved. Describe the role of this system in maintaining homeostasis.*

Multiple-Choice Questions

1. An atom's chemical properties are due to the number of
   (A) protons.
   (B) neutrons.
   (C) electrons.
   (D) ions.
   (E) moles.

2. Water's cohesive properties are most directly due to
   (A) nonpolar covalent bonds.
   (B) polar covalent bonds.
   (C) hydrogen bonds.
   (D) ionic bonds.
   (E) hydrophilic interactions.

3. A covalent double bond is made between an oxygen atom and a carbon atom. What is the most accurate description of the bond?
   (A) One electron is shared between the atoms.
   (B) Two electrons are shared equally between the atoms.
   (C) Four electrons are shared equally between the atoms.
   (D) Four electrons are shared unequally between the atoms.
   (E) Six electrons are shared unequally between the atoms.

4. _____ are substances that add protons to a solution, and _____ lower the proton concentration in a solution.
   (A) Anions; cations
   (B) Bases; acids
   (C) Acids; bases
   (D) Reactants; products
   (E) Atoms; compounds

5. In ionic bonds
   (A) electrons are transferred from one atom to another.
   (B) neutrons are transferred from one atom to another.
   (C) protons are transferred from one atom to another.
   (D) electrons are shared equally between two atoms.
   (E) electrons are shared unequally between two atoms.

6. Isotopes differ in their
   (A) number of protons.
   (B) number of neutrons.
   (C) number of electrons.
   (D) types of ions.
   (E) atomic numbers.

7. The molecular weight of carbon dioxide is 44.0098. One mole of carbon dioxide weighs exactly _____ grams.
   (A) 6.02×10^{23}
   (B) 22
   (C) 44
   (D) 44.0098
   (E) 88.02

8. An element's atomic number equals the number of _____ in the atom.
   (A) protons
   (B) protons plus electrons
   (C) neutrons
   (D) neutrons plus protons
   (E) neutrons plus electrons

9. One liter of a pH 4 solution contains _____ hydrogen ions (H^+).
   (A) 10^{-4}
   (B) 4×10^{-4}
   (C) 10^{-10} moles
   (D) 10^4
   (E) 10^{-4} moles

10. Sodium bicarbonate (baking soda) and carbonic acid are important buffers in the blood. When a small amount of acid is added to the buffer, the protons combine with the bicarbonate. What happens to the pH of the buffer?
    (A) It becomes more basic.
    (B) It becomes more acidic.
    (C) It does not change.
    (D) It becomes neutral.
    (E) It becomes acidic and then becomes more basic over time.

Free-Response Question

1. Water has many chemical and physical characteristics.
   (a) **Describe** how water's chemical structure determines these characteristics.
   (b) **Describe** three unique characteristics of water and discuss how these characteristics impact organisms.

Multiple-Choice Answers

1. (C) The electrons determine an atom's energy and its ability to participate in chemical bonds.
2. (C) Hydrogen bonds form between adjacent water molecules.
3. (D) Oxygen will share two electrons with carbon, and carbon will share two electrons with oxygen, forming a double bond. Oxygen is more electronegative than carbon; therefore, the covalent bonds will be polar.
4. (C) Acids add protons (H^+) while bases can take up protons.
5. (A) Electrons move from one atom to another and make two ions.
6. (B) Isotopes differ in the number of neutrons; isotopes vary in their atomic masses.