Chapter 4
Matter and Energy

4.1 Matter

Matter is regarded as any substance that occupies space; it exists in three states: solid, liquid, and gas (these states can undergo physical change as a result of heating or cooling where for example ice, water, and water vapor describe the different states of H_2O). Matter has properties by which it is recognized. We can identify some of these properties with the use of our senses: sight, touch, smell, taste. Other properties are described in the context of melting, boiling, and freezing points, density, electrical properties; the list goes on.

An element cannot be broken down into any other substance so that each element represents an original type of matter. Ninety-nine percent of the human body is made up of only six elements, oxygen (O), carbon (C), hydrogen (H), nitrogen (N), calcium (Ca), and phosphorous (P). Earth's matter is presently known to consist of 85 natural elements, all of which are displayed in the periodic table (Fig. 4.1).

Each element is made of the same kind of atom. Atoms consist of a densely packed nucleus containing positively charged protons (+) and neutrons that carry no charge. Negatively charged electrons ($-$) orbit the nucleus. Orbitals are said to inhabit discreet areas of space about the nucleus. Orbitals have distinct shapes and are located at specific distances from the nucleus. Atoms therefore consist of electrical charges and moving parts.

Electrons (e^-) that orbit closest to the nucleus are strongly attracted to the protons ($+$) within the nucleus (opposite charges attract); these are the core electrons – they do not react with other atoms. An atom also has valence electrons, with orbitals further from the nucleus than the core electrons. Valence electrons interact with other atoms (hydrogen, the first element on the periodic table, has one electron that is considered a valence electron; it does not have a core electron). The atoms of each element have specific properties of electronegativity (i.e., electron affinity or the ability to attract electrons) and electron arrangement (e.g., number of electron orbitals).

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PERIODIC TABLE OF THE ELEMENTS

IA	2A	3B	4B	5B	6B	7B	8 (VIII)	9 (VIII)	10 (VIII)	1B	2B	3A	4A	5A	6A	7A	8A
1 H 1.008																	2 He 4.003
3 Li 6.939	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
11 Na 22.99	12 Mg 24.312											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.9	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.71	29 Cu 63.546	30 Zn 65.37	31 Ga 69,72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.8
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (97)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.4	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.91	56 Ba 137.34	57* La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po 210	85 At 210	86 Rn 222
87 Fr 215	88 Ra 226.03	89** Ac 227.03	104 Rt [261]	105 Db [262]	106 Sg [266]	107 Bh [264]	108 Hs [269]	109 Mt [268]	110 [271]	111 [272]	112 [277]		114 [289]		116 [289]		

*Lanthanides	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm 145	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.5	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
**Actinides	90 Th 232.04	91 Pa 231	92 U 238.03	93 Np 237.05	94 Pu 239.05	95 Am 241.06	96 Cm 244.06	97 Bk 249.08	98 Cf 252.08	99 Es 252.08	100 Fm 257.1	101 Md 258.1	102 No 259.1	103 Lr 262.11

Gaseous at room temperature
Liquid at room temperature
Gallium melts at 29.78 deg. C.
Synthetic elements
All other elements are solid at room temperature

Fig. 4.1 Hundred and ten total elements are known (25 elements are man made). This periodic table of the elements is in the public domain and may be downloaded and printed without restriction (http://www.csudh.edu/oliver/chemdata/periodic/periodic-1.htm)

Molecules are combinations of atoms, as few as two atoms or perhaps as many as millions of atoms (e.g., a polymer). Much of what is known about molecules was derived from observations of collections of molecules called compounds. As an example, water is a compound of two hydrogen atoms and one oxygen atom – H_2O – whose molecular properties were largely derived from observations of many water molecules ($[H_2O]_n$) within a fixed container.

In addition to understanding molecules from observations of compounds, modern research and development has allowed us to better understand the interaction of chemical compounds by acknowledging the arrangement of the atoms within. Atomic and molecular arrangements dictate the energetic properties of matter.

4.2 Energy

Energy can be more difficult to conceptualize as compared with matter perhaps because of the limits of our senses; it is not always possible to quantify the energy held within a substance by holding, looking at, tasting or smelling it. Energy exists in several forms that include (but are not limited to) chemical, mechanical, electromagnetic, nuclear, light, and heat (thermal). Nutritionists and exercise physiologists often focus on chemical, mechanical, and heat exchanges that take place as the internal mechanisms within muscle cells perform work. Work entails a force, acting on an object, causing the object to be displaced:

$$W = fd$$

where W = work, f = force, d = displacement (or distance).

Energy can be defined as an ability to perform work or an ability to cause change so that lower energy states have less ability while high energy states have a greater ability to perform work or cause change. So how does energy content differ among atoms and molecules?

The most stable energy state for an atom occurs in its lowest energy state, when the valence electron shell is either completely filled or completely empty. Only a few elements are stable enough to exist as single atoms in their natural state: these are the noble or inert gases. Other atoms are more stable in molecular form; it takes two atoms of hydrogen (H), oxygen (O), and nitrogen (N) to form their respective and more stable molecules, H_2, O_2, and N_2.

An atomic or molecular system that has or has had force acting on it acquires energy. A system is in possession of mechanical energy if it is held in position or if it has motion.

Potential energy (PE) is stored energy; specifically, whenever an object that has mass holds a position within a field. A typical example of this is a weight held at a distance from the ground where:

$$\mathrm{PE} = mgh$$

where PE = potential energy, m = mass, g = earth's gravitation, and h = height. (The gravitational constant is $6.6742 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$.) The earth's gravitational field is relatively constant but potential energy can change by either altering the mass, the distance of the weight from the ground, or both.

Kinetic energy (KE) is found whenever an object with mass has velocity. Everything moving has kinetic energy:

$$\mathrm{KE} = \frac{1}{2}mv^2$$

where m = mass, v = velocity. Kinetic energy is changed by altering the mass of the object in motion, by varying that object's velocity, or both.

As mentioned previously, electrons "orbit" the nucleus in discreet areas of space. Energy is associated with the distance of the electron from the atomic nucleus. On such a small scale it might appear that atoms and molecules would hold little energy, but keep in mind, as Einstein informed us, this assumption would be false.

From an atomic perspective, kinetic energy can be envisioned as a rapidly orbiting electron around the nucleus of an atom. In actuality the electron does not travel along a fixed orbital path in a specific direction and so its exact movement cannot be traced. Conceptualizing the probable region where an electron might be is a more realistic endeavor as compared with calculating an electron's exact position so that electrons are better portrayed as regions of waves that surround the nucleus (rather than as orbitals). The kinetic energy of an atom is positive (+) and increases as the radius of the orbit decreases. The closer the wave is to the nucleus, the greater is the positive (+) kinetic energy (imagine swinging a ball around your head that is tethered by a string, the shorter the string, the faster the "orbit," and the greater the kinetic energy).

The potential energy of an atom is found as the attraction between the positively charged proton$^+$ in the nucleus and the negatively charged electron (e^-) "orbiting" the nucleus. The potential energy of an atom is negative (−):

$$\mathrm{PE} = (+1)(-1)/R = -1/R$$

In an atom with +1 proton and −1 electron, the product is −1. R = the distance between nucleus and electron.

Because opposite charges attract, the greater the distance between electron and nucleus the lower the negative (−) potential energy; the smaller the distance, the greater the negative (−) potential energy.

The total energy of an atom consists of the sum of its kinetic and potential energies:

$$\mathrm{TE} = \mathrm{KE} + \mathrm{PE}$$

where TE = total energy, KE = kinetic energy, PE = potential energy. Allowing for the attraction between electron and proton increases an atom's potential energy but as the electron's "orbital" radius decreases, kinetic energy increases. Atoms tend to exist in the lowest most stable energy state or ground state, where a balance is found between the (−) potential energy (proton and electron distance) and the (+) kinetic energy (the size of the electron "orbit" or wave). Because of this balance the astute student may recognize that an increase in kinetic energy, caused by a diminishing proton (+) and electron (−) distance, keeps the potential energy "in-check," preventing the nucleus and electron from collapsing into each other.

4.3 Internal Energy

Molecules are made of individual atoms so that interactions exist among multiple atomic nuclei and electron waves. The physicist, Richard Feynman (1918–1988) succinctly described molecular potential energy when he remarked that, "...all things are made up of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."

Feynman's elegant description reveals that part of the energy inherent to a molecule is a function of the distance between atomic nuclei and the molecular bond length. To illustrate bond length, remember that the closer an electron wave is to an atomic nucleus (or nuclei) the greater is the (−) potential energy. Also recall, that the smaller an electron "orbital" the greater is the (+) kinetic energy. However, within a molecule, as the positively charged nuclei of two or more atoms become closer, a repulsive force is found (like charges repel; opposite charges attract). To the contrary, incomplete valences invoke an attractive force between atoms. Taking these additional energies of repulsion and attraction into account, molecular bond formation takes place at a bond length where the total energy of the molecule is held at a minimum. Similar to atoms, molecules also tend to exist in the most stable energy state. Yet energy *is* there. Dependent on atomic make-up and molecular configurations then, matter contains various amounts of energy.

Heat is a form of energy, and so its impact on molecules must also be considered. Temperature is perhaps best known as a measurement of the hotness or coldness of an object. The kinetic energy of molecules governs the behavior of a gas. The average kinetic energy of a gas is proportional to its absolute temperature; the higher the temperature the greater the kinetic energy. Gas pressure and volume are related to the average molecular kinetic energy as represented by the ideal gas law:

$$PV = nRT$$

where $P =$ pressure, $V =$ volume, $n =$ moles of gas, $R =$ universal gas constant, $T =$ temperature. (R is a constant of proportionality at $8.314\,\mathrm{J\,K^{-1}}$ $(1.985\,\mathrm{cal\,{}^\circ C^{-1}})$.

A sealed container (a closed system) full of a known gas contains atoms (or paired atoms) that are moving about in random motion. These atoms are not bonding with each other and so the intermolecular forces described earlier are not present. Solids and liquids on the other hand are held together by chemical bonds and so they possess additional intermolecular forces.

Chemical energy is held within the intermolecular bonds that hold atoms together. There are several types of molecular bonds but it is the covalent bond that is of special interest from an available energy perspective. Covalent bonds exist as the sharing of valence electrons between two atoms (i.e., electrons that are both shared by and attracted to the nucleus of both atoms). The chemical energy of any given molecule is determined by the position of the atomic nuclei in respect to one another and subsequent electron density in accordance with bond types, bond lengths and bond angles.

Specific heat is the amount of heat required to raise the temperature of a unit mass one degree Celsius. It takes much more heat energy to raise the temperature of one gram of water as compared with say one gram of bone. Why is this? Molecular kinetic translational energy is the energy of linear motion; collisions between atoms and molecules that invoke linear changes in direction are measured as temperature. There are also molecular rotational and vibrational kinetic energies that contribute to a molecule's internal energy but these energies are not measured as temperature. Water has a higher specific heat as compared with many solids because when heat is added to water some of this energy goes toward increasing the molecular rotational and vibrational kinetic energy of the water molecules, energies that are not measured via temperature. The addition of heat to a solid acts to primarily increase the kinetic translational energy and is measured as temperature.

It is of interest that many animals, whether "cold-blooded" or "warm-blooded," tend to maintain body temperature at $\sim$36–40°C perhaps to influence or be influenced by the physical properties of the water they carry around (1). For example, the lowest amount of thermal energy required to raise the temperature of water one degree Celsius is near 36°C. Moreover, half of the influence that temperature has on the thermodynamic properties of water (as a solid, liquid, and gas) is found at 40°C.

It is common knowledge that temperature is measured by a device called a thermometer in units of degrees. But heat and temperature while related are not identical and so a different device is needed with units that are distinctly associated with heat energy. Heat is measured with a device called a calorimeter (see Chap. 14). Tradition has it that heat (energy) units were measured as calories but the more contemporary scientific international system (SI) quantifies heat as Joules. (Joules are discussed in more detail in the next section.) A calorie is defined as the amount of energy required to raise the temperature of one gram of water one degree Celsius, from 14.5°C to 15.5°C. A kilocalorie (kcal) refers to one liter of water and in lay terminology is interchangeable with the term calorie (cal). If one liter of water at 1,000 g (1 kg) were to be heated from 0°C to 10°C then:

$$10^{\circ}\mathrm{C} \times 1,000\,\mathrm{g} = 10,000\ \mathrm{cal\ or}\ 10\ \mathrm{kcal}$$

Because heat was *added* to the water we can go one step further and notate this heat increase with a positive sign as:

$$+10\ \text{kcal}$$

If 1 L (1,000 g or 1.0 kg) of water was cooled from 30°C to 20° then a 10° *loss* of heat from the water to the surroundings has taken place and is noted with a negative sign as:

$$-10^{\circ}\text{C} \times 1,000\,\text{g} = -10\ \text{kcal}$$

Put succinctly, systems may be comprised of atomic and molecular, kinetic, potential, work, and heat energies. Collectively these energies are known as the internal energy, symbolized as U, where U = internal energy.

4.4 Internal Energy (*U*) Exchanges

It is unfortunate that a simple and direct means of quantifying all of the individual energies that comprise the internal energy within a specific system is not yet available. For many students of chemistry this marks a point of retreat. But all is not lost. Energy always reveals itself when it undergoes change. And these changes are readily quantified in the form of heat and work. In fact, the study of thermodynamics evolved from the recognition that work and heat were related aspects of energy (*thermo* signifies heat energy; *dynamics* signifies change).

The fundamental relationship between heat and work was elegantly revealed by James Joules' (1818–1889) prolific experimentation with energy-exchange devices. One famous experiment was constructed as a paddle wheel in water that operated by a falling weight, an insulated water bath surrounded the apparatus and careful recordings of the water temperature took place. After a multitude of experiments, Joule revealed that 772 ft lb of falling weight caused the paddle wheels to agitate the water enough to produce a rise in temperature of one degree Fahrenheit (per pound of water). Joule's conclusion was a bold one: work and heat are interchangeable; energy *was* conserved!

Joule defined energy as matter in transition. Notice how the definition contains elements of both potential and kinetic energies: the word *transition* incites the term *kinetic energy*; the latent notion of potential energy arises from the implication of a starting position and the ending point of a transition. Joule described the presence of heat as energy in transition. This description too provides insight; when energy undergoes exchange, heat is lost to the environment. The heat exchanges between a system and its surroundings are used to describe energy exchange. Some examples of energy exchange and the devices that enable this to occur are provided in Table 4.1 (2).

Being interchangeable, work and thermal energy share the same unit, the Joule. Work is the amount of energy required to exert a force of one newton over a distance

Table 4.1 Energy exchange and the devices that enable the conversion

Energy exchange	Conversion device
Thermal to mechanical	Steam engine
Chemical to thermal	Burning coal
Chemical to electrical	Battery
Electromagnetic to thermal	Electric stove
Chemical to mechanical	Muscle

of one meter (one newton is the force that imparts a mass of one kilogram to an acceleration of one meter/second/second):

$$1\,\mathrm{J} = 1\,\mathrm{N\,m}$$

(This represents the energy required to lift 1 kg to a height of 10 cm)

Some other conversions:

$$1\,\mathrm{J} = 0.737562\,\mathrm{ft\ lb}$$
$$3{,}600\,\mathrm{J} = 1\,\mathrm{W\ h}$$
$$1\,\mathrm{J} = 0.239\,\mathrm{cal}$$
$$1\,\mathrm{cal} = 4.184\,\mathrm{J}$$

Heat (energy) can be lost from a system to its surroundings, decreasing the internal energy of the system. The opposite also is true. Thus, the addition or subtraction of heat to or from a system changes the internal energy:

$$\Delta U = \pm Q$$

where Δ = change, U = internal energy, $\pm Q$ = addition or loss of heat. Heat is not the only means of increasing internal energy. When work is added to a system in terms of a physical force, then similar to the addition of thermal energy, this too will increase the internal energy of the system. As an example, if a force were applied to a system from the surroundings or from a system to the surroundings, internal energy changes.

$$\Delta U = \pm W$$

where ΔU = change in internal energy, $\pm W$ = addition or loss of work.

It is understood that energy cannot be created or destroyed, that is the first law of thermodynamics. This means that if heat or work or both are added to a system, then the internal energy of that system must increase. If work or energy are taken away or subtracted from the system, then the internal energy of that system decreases. The following equation provides a mathematical description of energy exchange derived from the conservation of energy:

$$\Delta U = \pm Q + \pm W$$

References

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