5.1 Energy Changes in Chemical and Nuclear Reactions

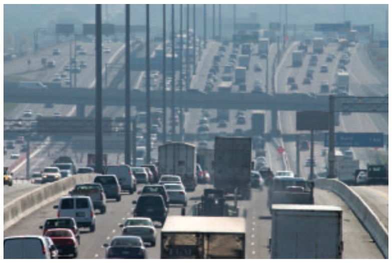


Figure 1 Our use of fossil fuels is unsustainable. New sources of green, sustainable energy are needed to meet the world's growing demand.

Our ability to harness energy has contributed greatly to the development of human civilization. For most of human history, the only way to transport people and things over land was by walking or through animal labour. Then, during the Industrial Revolution of the 1800s, inventors found ways to harness thermal energy to do work. Energy released by burning coal was used to heat water, releasing steam fast enough to move mechanical parts in machines. People and goods could then be moved long distances by steam-powered locomotives and boats. The next advance took place in the late 1800s in the form of the internal combustion engine, which produces energy by burning gasoline. Today, there are more than half a billion vehicles that are powered by the internal combustion engine (**Figure 1**). As this number grows, the demand for inexpensive and reliable sources of fuel also increases. Most of these vehicles use fossil fuels, which are non-renewable and negatively effect the environment. How will we meet our energy needs for transportation and other activities in more sustainable ways? To answer this challenge, we need to understand the energy changes that take place in chemical and nuclear reactions.

The Nature of Energy

thermochemistry the study of the energy changes that accompany physical or chemical changes in matter

energy the ability to do work; SI units joules (J)

work the amount of energy transferred by a force over a distance; SI units joules (J)

The study of energy changes during physical or chemical changes in matter is called **thermochemistry**. The study of thermochemistry uses some familiar terms in very precise ways. Scientists define **energy** as the ability to do work. **Work** is the energy transferred to an object by a force that causes the object to move. For example, the energy to lift satellites into orbit comes from simple chemical reactions that release huge quantities of thermal energy. The hot expanding gases released during the rocket launch do work on the rocket by pushing it into the sky. No work is done, however, if the force of the gases is inadequate to get the rocket off the ground. Both energy and work are measured in joules (J).

potential energy the energy of a body or system due to its position or composition

kinetic energy the energy of an object due to its motion

All forms of energy can be classified as either kinetic energy or potential energy. **Potential energy** is energy due to the position or composition of an object. **Kinetic energy** is the energy of motion. For example, the water behind a dam has a great deal of potential energy because of its elevation. This energy can be used to do work on the blades of turbines in a hydroelectric generating station. As the water falls, the potential energy is transformed into kinetic energy. The falling water causes the turbine blades to spin. The kinetic energy of the spinning turbines is transferred to a generator and transformed into electrical energy, another form of potential energy.

The energy associated with chemical bonds is also potential energy. Chemical bonds are the result of attractive forces between the nucleus of one atom or ion and the negative charges of electrons in the other atom or ion. The amount of energy released or absorbed in a chemical reaction equals the difference between the potential energy of the bonds in the reactants and the potential energy of the bonds in the products. For example, energy is released during the combustion of gasoline because the products have less potential energy than the reactants. In an internal combustion engine, the products of this combustion reaction are hot gases. The molecules in the hot gases that are produced by the engine move much faster than the molecules in the incoming cool air. Therefore, the combustion gases have more kinetic energy. This energy is used to do work on the mechanical parts inside the engine that eventually make the car move.

Thermal Energy, Heat, and Temperature

The total quantity of potential energy and kinetic energy of a substance is called **thermal energy**. In general, the quantity of thermal energy of a substance depends on how fast its entities—atoms, ions, molecules, or polyatomic ions—are moving. When a substance absorbs thermal energy, its entities move at a greater speed, and the substance warms up. When a substance releases thermal energy to its surroundings, its entities move more slowly, and the substance cools. In science, **heat** is a verb that refers to the transfer of thermal energy from a warm object to a cool object. So, when you heat water in a kettle on a stove, you transfer thermal energy from the burner to the kettle to the water. Similarly, when an object cools, it transfers thermal energy to its surroundings.

thermal energy the total quantity of kinetic and potential energy in a substance

heat the transfer of thermal energy from a warm object to a cooler object

Temperature is a measure of the average kinetic energy of the entities in a substance. As a substance is warmed, some of its particles move faster. The average kinetic energy of the substance's entities increases and so does the temperature of the substance. For example, a cup of hot water has a higher temperature than an iceberg. The average water molecule in the hot water has more kinetic energy than the average water molecule in the iceberg. However, an iceberg contains billions more water molecules than a cup of hot water. Therefore, the total quantity of thermal energy of an iceberg is greater than that of a cup of hot water.

temperature a measure of the average kinetic energy of entities in a substance

Law of Conservation of Energy

One important characteristic of energy is that it is always conserved. We cannot create new energy nor can we destroy energy by using it. Energy can only be converted from one form into another. Think about the combustion of propane in a barbecue (**Figure 2**). Chemical energy stored in propane is converted into thermal energy and light energy. However, the total amount of energy before and after the combustion reaction occurs remains constant. These ideas are summarized in the law of conservation of energy:

Figure 2 The potential energy of the propane fuel in the barbecue is converted to thermal energy.

Law of Conservation of Energy
Energy cannot be created or destroyed.

To help analyze energy conversions involving chemical reactions, chemists find it useful to divide the universe into two parts: the chemical system and its surroundings. A **chemical system** is composed of the reactants and products being studied. The **surroundings** are all the matter that is not part of the system. In the propane gas barbecue, the chemical system is composed of the reactants (propane gas, $C_3H_8(g)$, and oxygen gas, O_2 (g)), and the products (carbon dioxide gas, $CO_2(g)$, and water vapour, $H_2O(g)$). The surroundings include the barbecue and the food on the grill.

chemical system a group of reactants and products being studied

surroundings all the matter that is not part of the system

open system a system in which both matter and energy are free to enter and leave the system

closed system a system in which energy can enter and leave the system, but matter cannot

Chemical systems can be classified as being open or closed. An **open system** can exchange both energy and matter with its surroundings. An operating propane barbecue is an example of an open system. Propane gas flows into the burner and thermal energy and the products of combustion flow out. A chemical reaction that produces a gas in a solution in an unsealed beaker is also an open system, since energy and matter can flow into or out of the system to the surroundings. The surroundings include the beaker and the air around the beaker. A **closed system** can exchange energy, but not matter, with its surroundings. A glow stick (**Figure 3**) is an example of a closed system. Light energy released when chemicals inside the stick are mixed flows out into the surroundings. The matter (that is, the chemicals) remain sealed inside.

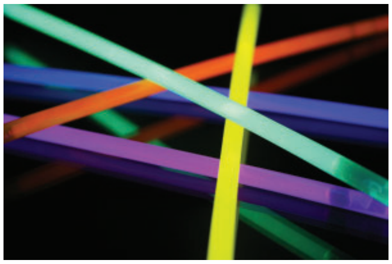


Figure 3 Each of these glow sticks forms a closed system. Matter cannot escape; only light energy.

A third kind of system exists, called an isolated system. In an **isolated system**, neither matter nor energy can move into or out of the system. However, it is impossible to set up a true isolated system on Earth.

isolated system an ideal system in which neither matter nor energy can move in or out

Endothermic and Exothermic Reactions

During a chemical reaction, the chemical bonds in the reactant(s) are broken, and new bonds are formed to produce the product(s). The potential energy of the entities in a stable structure, such as the atoms in a molecule or the ions in an ionic compound, is lower than the potential energy of the individual isolated atoms. Therefore, bond breaking requires energy, while bond formation releases energy.

From the law of conservation of energy, you know that the total energy in a chemical system and its surroundings must be the same before and after a chemical reaction occurs. If more energy is released from the formation of new bonds in the products than is required to break bonds in the reactants, then the chemical reaction will release some energy to the surroundings. A chemical reaction system that releases energy to the surroundings is **exothermic** (the prefix *exo-* means "out of"). The products of an exothermic reaction have lower potential energy (and stronger bonds on average) than the reactants.

exothermic releasing energy to the surroundings

For example, the combustion of methane is an exothermic reaction. The balanced chemical equation for this reaction is

$$CH_4(g) + 2\,O_2(g) \rightarrow CO_2(g) + 2\,H_2O(g) + \text{energy}$$

Notice that an energy term is included on the product side of the equation to show that energy is released. This energy is the difference between the energy absorbed by breaking bonds in the reactants and the energy released by forming bonds in the products. The quantity of this energy is the difference in potential energy between the reactants and products and has the symbol ΔE_p. Since the combustion of methane is exothermic, energy is released to the surroundings, mainly as thermal energy and light energy. **Figure 4** illustrates the changes that occur during this reaction in an open system. The quantity of matter in the system (represented by the tan box) remains the same, and the released energy (the large arrow) flows to the surroundings (the yellow area). When an exothermic reaction releases thermal energy, the temperature of the surroundings increases.

Energy Changes during an Exothermic Reaction in an Open System

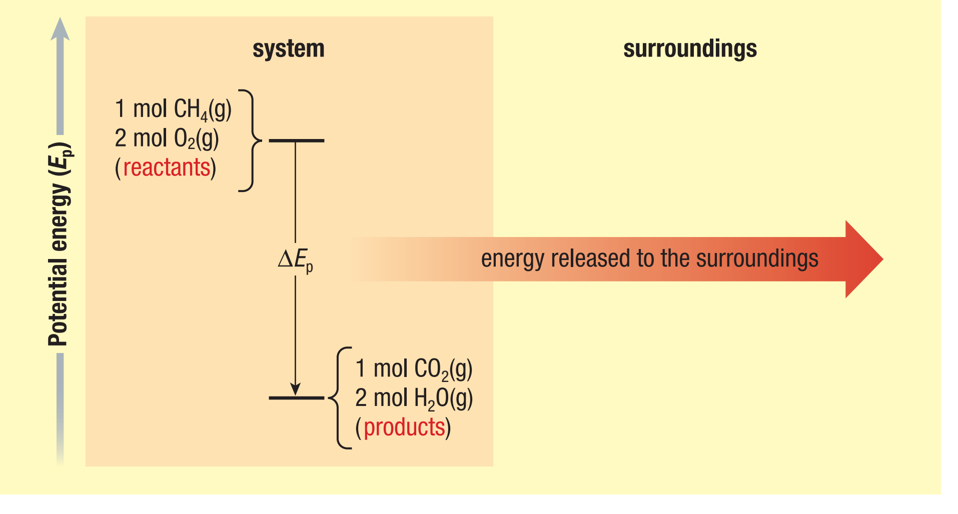


Figure 4 The combustion of methane releases a quantity of energy with the magnitude ΔE_p, which flows to the surroundings, mainly as thermal energy and light energy. This is an exothermic reaction.

endothermic absorbing energy from the surroundings

A reaction that absorbs thermal energy from its surroundings is **endothermic** (the prefix *endo-* means "inside"). During an endothermic reaction, the chemical system absorbs energy from the surroundings and increases its potential energy. This means that the products have higher potential energy (and weaker bonds on average) than the reactants. The synthesis of nitric oxide from its elements is an example of an endothermic reaction, represented by the equation

$$N_2(g) + O_2(g) + \text{energy} \rightarrow 2\,NO(g)$$

Notice that, for an endothermic reaction, the energy term is included on the reactants side of the equation. **Figure 5** illustrates the changes that occur during this reaction in an open system. The quantity of matter in the system again remains the same, but now energy flows from the surroundings to the system.

Energy Changes during an Endothermic Reaction in an Open System

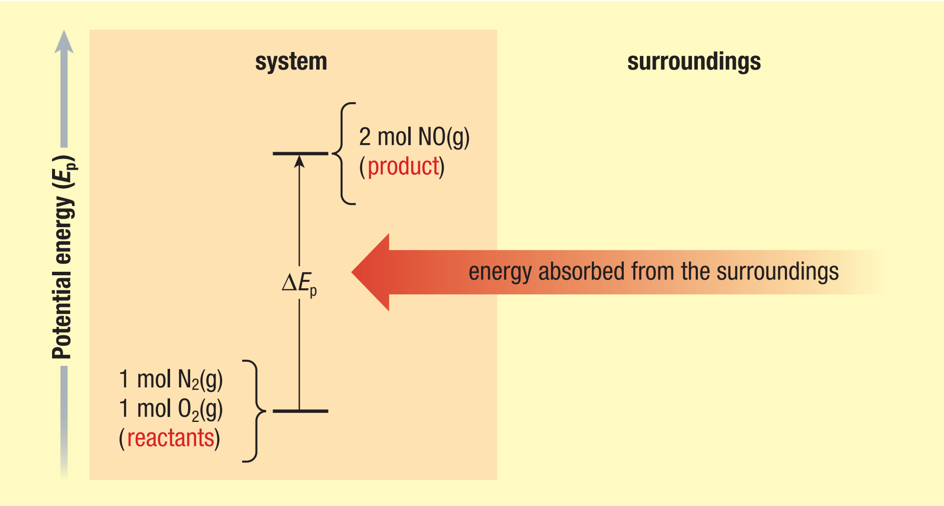


Figure 5 The synthesis of nitric oxide from its elements absorbs a quantity of thermal energy with the magnitude ΔE_p from the surroundings. This is an endothermic reaction.

UNIT TASK BOOKMARK

How can you apply what you have learned about endothermic and exothermic reactions in your Unit Task (on page 402)?

Nuclear Energy

Unlike chemical reactions, all nuclear reactions are exothermic. Per unit of mass, nuclear reactions release much more energy than exothermic chemical reactions. Two nuclear reactions involving large quantities of energy are fission and fusion.

A **fusion** reaction occurs when nuclei of small atomic mass combine to form larger, heavier nuclei. Fusion reactions are responsible for the release of vast amounts of energy in stars, including the Sun (**Figure 6**). The Sun consists of 73 % hydrogen, 26 % helium, and 1 % other elements. Hydrogen nuclei under immensely high pressure in the Sun undergo fusion and form helium nuclei. The fusion process releases energy, some of which reaches Earth. The fusion of hydrogen atoms produces 1.7×10^9 kJ of energy for each mole of helium produced.

fusion the process of combining two or more nuclei of low atomic mass to form a heavier, more stable nucleus

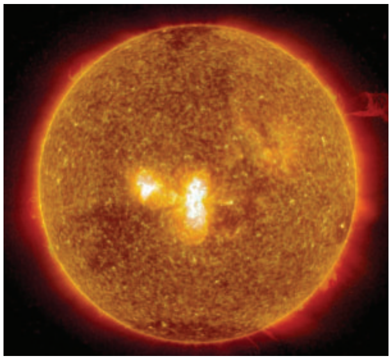


Figure 6 The most common fusion reactions that occur in the Sun involve hydrogen atoms.

Let us review nuclear notation. An element with the chemical symbol X is represented as ${}^{A}_{Z}X$, where A is the mass number (number of protons plus number of neutrons) and Z is the atomic number (number of protons). A neutron is a subatomic entity, and the symbol ${}^{1}_{0}n$ is used to show that a neutron has a mass number of 1 and an atomic number of 0. Using nuclear notation, the equation for the fusion reaction of hydrogen atoms is

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

Scientists have worked for decades to find a way to develop fusion reactors to generate energy, but the intense pressure and heat needed for fusion to occur have made this difficult to achieve to date. CAREER LINK

During **fission**, large nuclei with high atomic mass are split into smaller, lighter nuclei by collision with a neutron. The nuclei of all elements above atomic number 83 are unstable and can undergo fission. Fission does not normally occur in nature. Fission reactions produce vast quantities of energy—millions of times more than is released in chemical reactions.

fission the process of using a neutron to split a nucleus of high atomic mass into two nuclei with smaller masses

Nuclear power plants use the fission of uranium-235 to produce electricity. When a neutron collides with a $^{235}_{92}U$ nucleus, the uranium nucleus splits into smaller nuclei and releases energy and additional neutrons (**Figure 7**). These neutrons collide with more uranium nuclei, causing these nuclei to split and release more energy and even more neutrons.

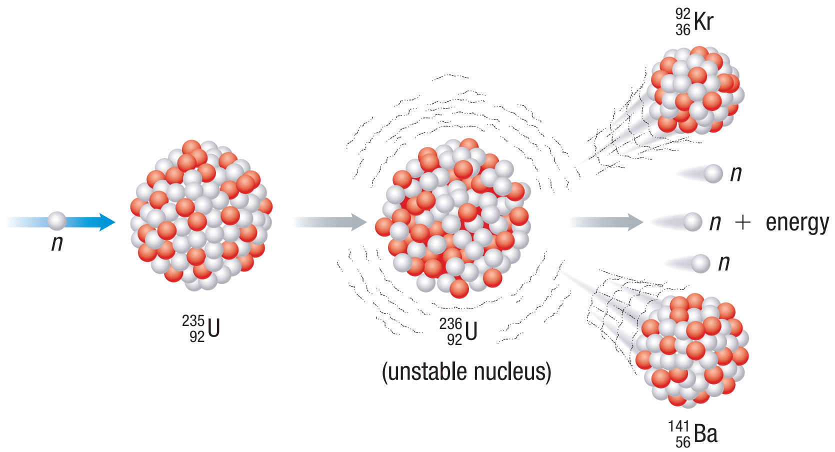


Figure 7 The uranium-235 nucleus undergoes fission when a neutron strikes it. The fission produces two lighter nuclei, free neutrons, and a large amount of energy.

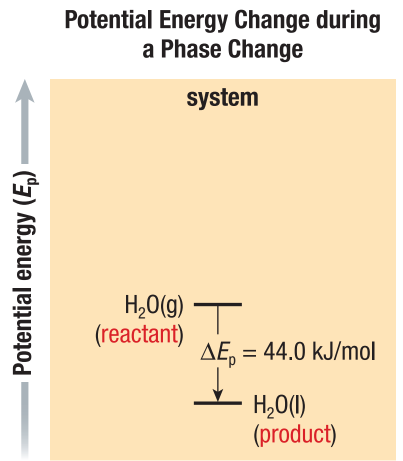
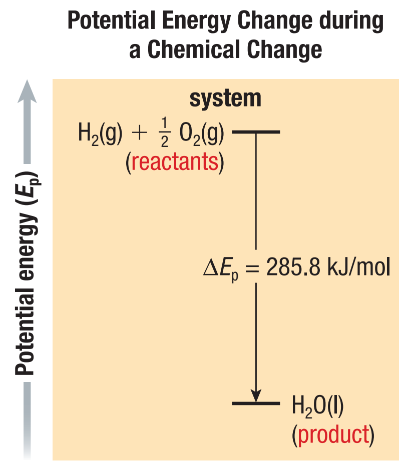
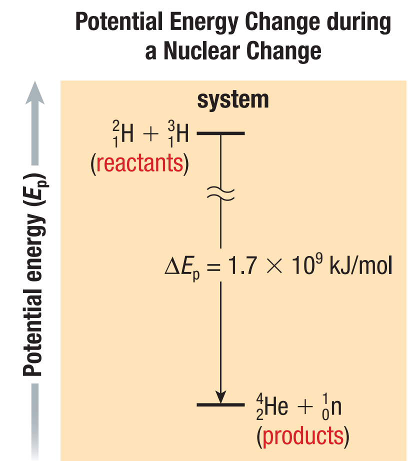
The equation for the fission of uranium is

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3\ ^{1}_{0}n$$

Uranium is used in nuclear power plants because it undergoes a fission chain reaction. About 15 % of all electrical energy in Canada is produced by the fission of uranium in nuclear power plants. Nuclear power plants can generate much more electricity from a small amount of fuel than can power plants that use fossil fuels. For example, uranium fission can produce about 26 million times more energy than the combustion of an equal mass of methane. WEB LINK

Energy changes occur during any physical, chemical, or nuclear change. **Table 1** gives an example of each of these types of energy changes, and the magnitude of the potential energy change in the system. Notice that the potential energy change varies considerably. For example, to show the graph of the nuclear change on the same scale as the other changes would require a textbook about 1000 km long!

Table 1 Examples of Magnitudes of Potential Energy Changes during a Phase Change, Chemical Change, and Nuclear Change

Phase change	Chemical change	Nuclear change
$H_2O(g) \rightarrow H_2O(l)$	$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$	$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$
		

5.1 Review

Summary

- Energy is the ability to do work.
- Potential energy is the energy of position or composition.
- Kinetic energy is the energy of motion.
- Thermal energy is the sum of the potential and kinetic energy in a substance.
- Heat is the transfer of thermal energy from a warmer object to a cooler object.
- Temperature is a measure of the average kinetic energy of the particles in a substance.
- The law of conservation of energy states that energy cannot be created or destroyed but can be converted from one form to another.
- An open system can exchange both energy and matter with its surroundings. A closed system can exchange energy, but not matter, with its surroundings.
- An exothermic reaction releases energy to its surroundings. An endothermic reaction absorbs energy from its surroundings.
- Fusion is a nuclear reaction in which two or more nuclei of low atomic mass combine to form a heavier nucleus.
- Fission is a nuclear reaction in which a neutron collides with a nucleus of high atomic mass and splits it into nuclei with smaller masses.

Questions

1. For each of the following, describe which is greater—the potential energy or the kinetic energy. K/U
   (a) a stick of dynamite prior to exploding
   (b) a space shuttle before launch
   (c) the soot rising above a campfire
   (d) the chemicals inside a new battery
2. For each of the following, identify whether the reaction process is exothermic or endothermic. K/U
   (a) water evaporating into steam
   (b) a candle burning
   (c) the combustion of gasoline
   (d) the melting of ice
   (e) the splitting of a nitrogen molecule, N_2, into individual atoms
   (f) dissolving barium hydroxide, $Ba(OH)_2$, in water and observing a temperature decrease in the surroundings
3. Consider the following statement: "The law of conservation of energy states that energy cannot be created or destroyed. Therefore, when thermal energy is transferred from a system to the surroundings, the quantity of thermal energy lost by the system must be equal to the amount of thermal energy gained by the surroundings." Does this statement accurately describe what happens to the thermal energy? Explain why or why not. K/U A
4. Distinguish between heat, thermal energy, and temperature using examples from your experience. K/U A
5. Compare and contrast nuclear fission and fusion. K/U T/I
6. The law of conservation of energy can be stated as "the total energy of the universe is constant." Explain how this is a restatement of the definition given in the text. K/U T/I
7. A fire is started in a fireplace by striking a match and lighting crumpled paper under some logs. Explain all the energy transfers in this scenario using the terms "exothermic," "endothermic," "system," "surroundings," "potential energy," and "kinetic energy." K/U T/I A
8. Explain why the water in a swimming pool at 24 °C has more thermal energy than a cup of boiling water at 100 °C. K/U T/I A
9. Liquid water at 0 °C turns to ice. Is this process endothermic or exothermic? Explain what is occurring using the terms "system," "surroundings," "thermal energy," "potential energy," and "kinetic energy." K/U T/I A