Chapter Fourteen NUCLEAR ENERGY

KEY IDEAS

The main components of the atomic nucleus are protons and neutrons, also called nucleons. The atomic number of an atom is the number of protons its nucleus contains; the mass number is the sum of the numbers of protons and neutrons in the nucleus.

Isotopes are atoms with the same atomic numbers but differing mass numbers. The unit of atomic mass is based on the isotope carbon-12. One atomic mass unit is equivalent to 931 million electron-volts of energy. The mass of a nucleus is always less than the mass of its individual nucleons. The energy equivalent of this lost mass is related to the stability of the nucleus. Inside the nucleus, the existence of short-range forces contribute to this stability.

A nuclear reaction involves changes in one or more atomic nuclei. Nuclear equations represent nuclear reactions. A nuclear equation is balanced when the atomic and mass numbers agree on both sides of the arrow.

Radioactive decay is a series of naturally occurring nuclear reactions, which occur in order to increase the stability of the resulting nuclei. In alpha decay, alpha particles are ejected from the nucleus. In beta decay and positron emission, negative and positive beta particles, respectively, are ejected from their parent nuclei. In electron capture, a nucleus absorbs one of the inner electrons surrounding it. In gamma decay, a nucleus ejects a gamma photon, thereby lowering the nuclear energy.

Radioactive decay occurs according to strict mathematical laws. As a result, the half life of a radioactive substance, that is, the amount of time required to reduce a sample of the substance to one-half its initial value, is constant under all conditions.

Nuclear reactions can by induced by bombarding nuclei with subatomic particles such as alpha particles. The energies of the bombarding particles needed to produce a reaction are achieved by introducing the particles into a particle accelerator such as a cyclotron. Only charged particles may be accelerated in this way.

It is now known that the proton and the neutron are not fundamental particles. The existence of these nucleons and other nuclear particles has been explained by the presence of six varieties of particles called *quarks*. The electric charge on these particles is either $-\frac{1}{3}$ or $+\frac{2}{3}$ of the elementary charge.

KEY OBJECTIVES

At the conclusion of this chapter you will be able to:

- Define the term *nucleon,* and distinguish between the two nucleons.
- Interpret the parts of nuclear symbol, and define the terms *atomic number, mass number,* and *isotope.*
- Define the terms *mass defect* and *binding energy*, and explain how they contribute to the stability of the nucleus.
- Explain how nuclear forces differ from gravitational and electromagnetic forces.
- Balance a nuclear equation.
- List examples of nuclear reactions that occur naturally.
- Describe various types of induced nuclear reactions.
- Describe how quarks are involved in nuclear structure.

14.1 INTRODUCTION

After British physicist Ernest Rutherford proposed his nuclear model in the early part of the twentieth century, physicists began to question whether the nucleus had a structure of its own. At present, there is still no complete answer to this question. By the mid-1930s, however, a simple nuclear model was in place and we will examine that model in this chapter.

✱ 14.2 NUCLEONS

The components of the nucleus are called **nucleons** and are described by a number of properties, including electric charge. Nuclear charge is usually measured in terms of the elementary charge (e) rather than the coulomb.

Two of the principal nucleons are the *proton* and the *neutron*. The proton has a charge of $+1e$, and the neutron is uncharged.

✱ indicates that material is part of the New York State core curriculum.

14.3 NUCLEAR SYMBOLS

All atomic nuclei (also called *nuclides*)—and their component nucleons—may be represented by the same general symbol:

$$^{A}_{Z}X$$

The letter X represents the letter(s) used to identify the particle; the letter *Z*, representing the **atomic number**, indicates the number of elementary charges present (assumed to be positive unless a negative sign is written); and the letter *A*, representing the **mass number**, is equal to the sum of neutrons and protons present.

The number of neutrons (*N*) present in an atomic nucleus is given by this expression:

PHYSICS CONCEPTS

$$N = A - Z$$

Using this representation, we can write the symbols for the proton, neutron, and electron, respectively, as follows:

$^{1}_{1}H$ (proton) $^{1}_{0}n$ (neutron) $^{0}_{-1}e$ (electron)

The symbol for the proton is a result of the fact that a proton is the nucleus of the simplest hydrogen atom. While the electron is not normally considered a nuclear particle, there are occasions when it is produced in the nucleus.

PROBLEM

Identify the nucleons present in the atomic nucleus whose symbol is $^{22}_{10}Ne$.

SOLUTION

The atomic number of neon (Ne [illegible] efore, the nucleus contains 10 protons.

The mass number of this nucle [illegible] efore, the nucleus contains 22 protons and neutrons.

The number of neutrons is fo [illegible] cting the atomic number from the mass number:

22 protons and neutr [illegible] ons = 12 neutrons.

PROBLEM

Calculate the number of protons and neutrons in these nuclei: (a) ${}_{1}^{2}H$ and (b) ${}_{1}^{3}H$.

SOLUTION

(a) ${}_{1}^{2}H$ contains 1 proton and 1 neutron.

(b) ${}_{1}^{3}H$ contains 1 proton and 2 neutrons.

14.4 ISOTOPES

All the nuclei in a sample of a given element contain the same number of protons. They may, however, contain different numbers of neutrons. Nuclei that have the same atomic number but have different mass numbers are called **isotopes**. For example, ${}_{1}^{1}H$, ${}_{1}^{2}H$, and ${}_{1}^{3}H$ are all isotopes of the element hydrogen. Sometimes an isotope is written without its atomic number (${}^{22}Ne$) or with the name of its element and its mass number (hydrogen-2).

♠ 14.5 NUCLEAR MASSES

Since nuclear particles have very small masses, they are usually measured in terms of the *atomic mass unit* (u) rather than the kilogram. The proton and the neutron each have an approximate mass of 1 atomic mass unit, although the neutron is slightly more massive than the proton. The basis of the nuclear-mass scale is the isotope carbon-12, and an *atom* of this isotope is assigned an exact mass of 12 atomic mass units. One atomic mass unit is approximately equal to 1.66×10^{-27} kilogram.

Equivalents of Nuclear Masses

Nuclear masses may also be expressed in terms of their *energy equivalents*. Using Einstein's famous mass-energy relationship ($E = mc^2$), it can be shown (see the next problem) that 1 atomic mass unit of mass is equivalent to 931 mega-electron-volts of energy.

PROBLEM

Calculate the energy equivalent (in MeV) of 1 atomic mass unit of mass.

SOLUTION

Mass Defect and Binding Energy

A nucleus such as $^{56}_{26}Fe$ contains 26 (positive) protons concentrated in an extremely small space. We might suppose that the repulsion of the positive charges ought to tear the nucleus apart. However, this nucleus is quite stable. To explain the reason, we need to compare two quantities: the mass of the nucleus itself and the total mass of its nucleons.

PROBLEM
Compare the mass of a $^{56}_{26}Fe$ nucleus (mass = 55.9206 u) with the total mass of its nucleons.

SOLUTION
Using the preceding table and t [illegible] hat this nucleus contains 26 protons and 30 neutrons (why?), we can [illegible] s the total mass of the nucleons:

Mass of 26 protons	=	[illegible] 07276 u)	= 26.1392 u
Mass of 30 neutrons	=	[illegible] 08665 u)	= 30.2600 u
Total mass of nucleons			= 56.4492 u

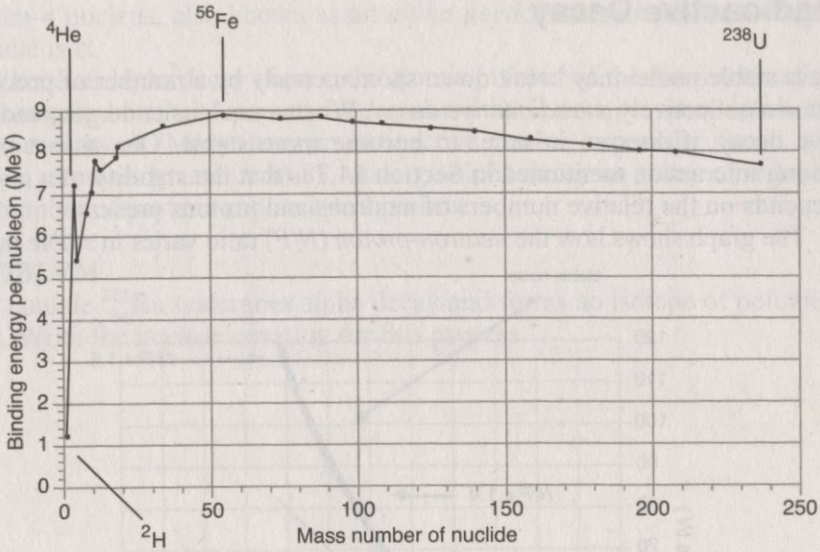
Subtracting the two values (56.[illegible] 55.9206 u), we see that the mass of the nucleus is 0.5286 u *less* than [illegible] s of its nucleons.

The mass difference that we [illegible] ulated is known as the mass defect of the nucleus. Its energy equi[illegible] approximately 492 mega-electron-volts (How can we calculate thi[illegible] ?) and is called the *binding energy* of the nucleus. The binding ene[illegible] nucleus is the amount of energy that must be added in order to separ[illegible] ucleus into its component nucleons.

14.6 AVERAGE BINDING ENERGY PER NUCLEON

One way of estimating the stability of a nucleus is by referring to a quantity known as the average *binding energy per nucleon*. It is calculated by dividing the total binding energy of the nucleus by the number of nucleons present (i.e., the mass number). In the problem in Section 14.5, the binding energy of 492 mega-electron-volts is divided by 56 nucleons to yield 8.79 mega-electron-volts per nucleon. In general, the larger the binding energy per nucleon, the more stable is the nucleus.

The graph below illustrates how the binding energy per nucleon varies with the number of nucleons in a nucleus. The nuclei located toward the center of the graph (e.g., ^{56}Fe) have larger values than the nuclei located at either end (e.g., ^{2}H and ^{238}U). In Section 14.10, we will see how some of the less stable nuclei can be used in the production of energy.



14.7 NUCLEAR FORCES

The stability of a nucleus is tied to the existence of two *nuclear forces*. These forces, called the *strong* and *weak interactions*, are much more powerful at the very small distances present within the nucleus than are gravitational or electromagnetic forces. At larger distances, however, the strong and weak interactions lose their effectiveness, and for this reason they are called *short-range forces*.

14.8 NUCLEAR REACTIONS

Nuclear Equations

A nuclear reaction is a change that occurs within or among atomic nuclei and is represented by a *nuclear equation*, such as the following:

$$^{15}_{7}\text{N} + ^{1}_{1}\text{H} \rightarrow ^{12}_{6}\text{C} + ^{4}_{2}\text{He}$$

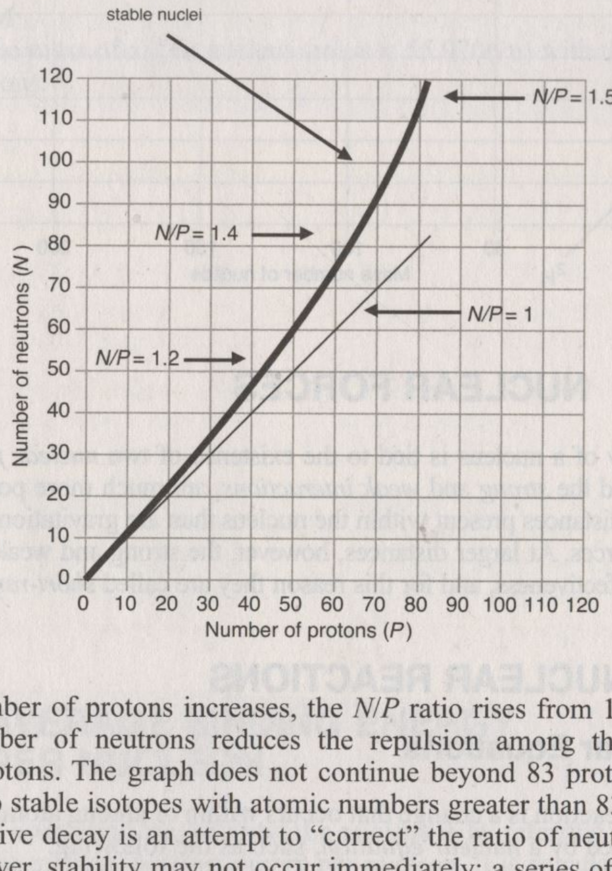
If we examine this equation carefully, we note that the sum of the atomic numbers on the left side (7 + 1) equals the sum of the atomic numbers on the right side (6 + 2). This equality demonstrates the fact that electric charge must be conserved in a nuclear reaction. Similarly, the sum of the mass numbers on the left side of the equation (15 + 1) equals the sum of the mass numbers on the right side (12 + 4).

This nuclear equation is considered to be *balanced* because both charge and mass number are conserved. All of the nuclear equations we write will be balanced equations.

Radioactive Decay

Less stable nuclei may break down spontaneously by a number of processes known collectively as *radioactive decay*. When a nucleus undergoes radioactive decay, it does so in order to become more stable. One aspect of the strong interaction mentioned in Section 14.7 is that the stability of a nucleus depends on the relative numbers of neutrons and protons present.

The graph shows how the *neutron-proton* (*N*/*P*) ratio varies in *stable* nuclei.



As the number of protons increases, the *N*/*P* ratio rises from 1 to 1.5. The larger number of neutrons reduces the repulsion among the positively charged protons. The graph does not continue beyond 83 protons because there are no stable isotopes with atomic numbers greater than 83.

Radioactive decay is an attempt to "correct" the ratio of neutrons to protons. However, stability may not occur immediately; a series of decay reactions may be required before a stable nucleus is finally produced.

ALPHA DECAY

The following nuclear reaction:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

is an example of *alpha decay*. The uranium-238 nucleus (the *parent nucleus*) breaks down to produce a thorium-234 nucleus (the *daughter nucleus*) and a helium-4 nucleus, also known as an *alpha particle*. A symbol for the alpha particle is α.

Whenever alpha decay occurs, the atomic number of the daughter nucleus (as compared with its parent) is *decreased* by 2 and its mass number is *decreased* by 4. Many heavier radioactive nuclei, especially those with atomic numbers greater than 83, undergo alpha decay as a way of reducing the number of protons and neutrons present.

PROBLEM
The nuclide $^{222}_{86}Rn$ undergoes alpha decay and forms an isotope of polonium (Po). Write the nuclear equation for this process.

SOLUTION
Our problem is to find the atomic a[illegible]mbers of the Po nuclide. We write the alpha decay as follows:

$$^{222}_{86}Rn \rightarrow \text{[illegible]}$$

Since the atomic and mass numbers [illegible]ual on both sides of the equation, the atomic number of polonium [illegible] and the mass number of this nuclide must be 218. Therefore, we c[illegible]rite the complete equation:

$$\text{[illegible]} He$$

Beta (–) Decay

Certain nuclei undergo radioactive decay and produce an *electron*, also known as a *beta* (–) *particle*, in the reaction. A symbol for the beta (–) particle is β^-.

Beta decay is governed by the weak interaction mentioned in Section 14.7. The following equation illustrates the process of beta (–) decay:

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e$$

In beta (–) decay, the atomic number of the daughter is increased by 1 while its mass number remains unchanged. Beta (–) decay occurs in nuclei whose *N/P* ratios lie *above* the band of stability illustrated in the graph on page 425.

Actually, another subatomic particle, called an *antineutrino* is also produced in beta (–) decay. Even though charge and mass number are conserved, an antineutrino must be produced in order to conserve momentum and energy as well.

The antineutrino is an example of an *antiparticle*. Every subatomic particle is associated with its own unique antiparticle. Particles and their antiparticles have the same mass, but their electric charges are *opposite* in sign. If a particle and its antiparticle are brought into contact, all of the mass is transformed entirely into electromagnetic energy in the form of two gamma-ray photons.

PROBLEM

The nuclide $^{14}_{6}C$ undergoes beta (–) decay and forms an isotope of nitrogen (N). Write the nuclear equation for this process.

SOLUTION

Our problem is to find the atomic and mass numbers of the N nuclide. We will write the beta (–) decay as follows:

$$^{14}_{6}C \rightarrow ^{A}_{Z}N + ^{0}_{-1}e$$

Since the atomic and mass numbers must be equal on both sides of the equation, the atomic number of nitrogen must be 7 and the mass number of this nuclide must be 14. Therefore, we can now write the complete equation:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$

Note that the *N/P* ratio of the parent nucleus (^{14}C) is 1.33 (8/6), while the *N/P* ratio of the daughter nucleus (^{14}N) is 1.00 (7/7). Therefore, beta (–) decay is a process that *decreases* the *N/P* ratio.

Positron Decay

The name *positron* is a combination of the word parts positive electron. The positron is the *antiparticle* of the electron. The symbol for the positron is $^{0}_{+1}e$; another symbol for the positron is β^+.

The following equation is an example of positron decay:

$$^{19}_{10}Ne \rightarrow ^{19}_{9}F + ^{0}_{+1}e$$

In positron decay, the atomic number of the daughter nucleus is *decreased* by 1 while its mass number remains *unchanged*. An additional particle (called the *neutrino* and symbolized as ν) is also produced in positron decay in order to conserve energy and momentum.

If we examine the *N/P* ratios of the parent and daughter nuclei in the equation given above, we see that positron decay *increases* the *N/P* ratio.

Electron Capture

This type of reaction occurs when a nucleus captures one of the inner electrons orbiting the atom. In this reaction, a neutrino is also produced. The following equation is an example of electron capture:

$$ {}^{7}_{4}\text{Be} + {}^{0}_{-1}\text{e} \rightarrow {}^{7}_{3}\text{Li} $$

Electron capture also serves to *increase* the *N/P* ratio of nuclei.

Gamma Decay

Like the electrons in an atom, the nucleus contains energy levels. Occasionally, a nucleus will enter an excited state, known as a *metastable* state. We symbolize a metastable nucleus by adding an *m* to its mass number (e.g., 99m). Eventually, the nucleus will return to its normal state and then a high-energy gamma-ray photon will be emitted.

The symbol for the gamma-ray photon is γ. The following equation is an example of gamma decay:

$$ {}^{99m}_{43}\text{Tc} \rightarrow {}^{99}_{43}\text{Tc} + \gamma $$

14.9 INDUCED NUCLEAR REACTIONS

All of the nuclear reactions we have studied so far have been *natural* processes. We now turn our attention to nuclear changes that have been produced artificially or *induced*. To induce a nuclear reaction, a target nucleus is bombarded with a nuclear particle.

Particle Accelerators

A *particle accelerator* is a device that uses electric and magnetic fields to provide a charged bombarding nuclear particle with sufficient kinetic energy to induce the desired nuclear reaction. As an analogy, consider a bullet fired at a wall at a speed of 10 miles per hour. At this slow speed, the kinetic energy of the bullet would have hardly any effect on the wall. If the bullet were fired at 600 miles per hour, however, its effect on the wall would be devestating!

Examples of modern particle accelerators include the *Van de Graaff accelerator*, the *linear accelerator*, the *cyclotron*, the *synchrotron,* and the *large electron-positron (LEP) collider*. These devices can supply bombarding particles with kinetic energies ranging from 10^3 to 10^{12} electron-volts.

Artificial Transmutation

The first induced nuclear reactions used alpha particles (because of their large masses) as the bombarding particles. In 1919, Rutherford bombarded nitrogen-14 nuclei with alpha particles and noted that protons were emitted. In this reaction:

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{1}_{1}H + ^{17}_{8}O$$

nitrogen-14 was artificially changed or *transmuted* into oxygen-17. In 1932, English physicist Sir James Chadwick bombarded beryllium-9 and identified a stream of uncharged particles that we now call *neutrons*. The reaction is shown below:

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{1}_{0}n + ^{12}_{6}C$$

In 1934, French physicists Frédéric Joliot-Curie and Irène Joliot-Curie bombarded aluminum-27 and produced the first artificially radioactive isotope, phosphorus-30:

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{1}_{0}n + ^{30}_{15}P$$

The phosphorus-30 undergoes positron decay (see page 428) and forms silicon-30.

14.10 FUNDAMENTAL PARTICLES AND INTERACTIONS

The model of nuclear structure continues to evolve. Over the years, as physicists probed the nucleus, a host of particles were discovered whose functions were largely unknown. In an attempt to explain the existence of these particles, a number of theories were developed.

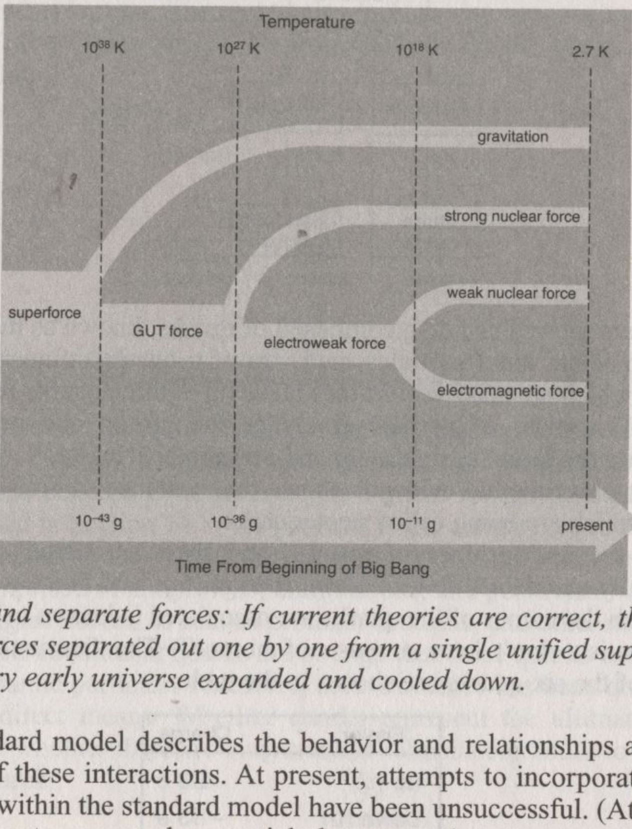
One of the most successful models is known as the *standard model*, which assumes that four fundamental interactions (also known as fundamental forces) operate in the universe: *electromagnetic*, *weak*, *strong*, and *gravitational*.

FUNDAMENTAL FORCES

Interaction	Relative Strength	Range	Mediating Particle
Strong	1	Short	Gluon
Electromagnetic	0.0073	Long	Photon
Weak	10^{-9}	Very short	W,Z Boson
Gravitational	10^{-38}	Long	Graviton

As can be ascertained from the table above, the four fundamental forces in our present Universe are distinct and have very different characteristics. The current thinking in theoretical physics is that this was not always the case. There is a strong belief (yet to be confirmed experimentally) that in the very early Universe when temperatures were very high compared with today, the weak, electromagnetic, and strong forces were unified into a single force. Only when the temperature dropped did these forces separate from each other, with the strong force separating first and then at a still lower temperature the electromagnetic and weak forces separating, leaving us with the four distinct forces we see in our present Universe. The process of the forces separating from each other is called **spontaneous symmetry breaking**.

There is further speculation, which is even less firm than that above, that at even higher temperatures all four forces were unified into a single force.



Unified and separate forces: If current theories are correct, the individual forces separated out one by one from a single unified superforce as the very early universe expanded and cooled down.

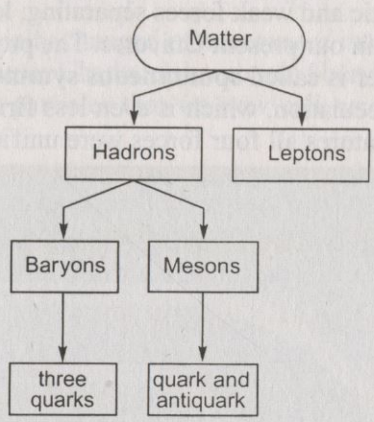
The standard model describes the behavior and relationships among the first three of these interactions. At present, attempts to incorporate gravitational force within the standard model have been unsuccessful. (At this writing, experiments on a nuclear particle known as the *muon* suggest that the standard model might need to be reformulated in order to explain the results of the experiments.)

An important feature of the standard model is the recognition that there are fundamental particles, known as quarks, which have *fractional elementary charges* and are the building blocks of protons, neutrons, and other nuclear particles.

Particles that interact by the strong interaction are called hadrons. This general classification includes mesons and baryons, but specifically excludes leptons, which do not interact by the strong force. The weak interaction acts on both hadrons and leptons.

The chart below, which is included on the Reference Tables, summarizes the relationship between these different particles of matter.

Classification of Matter



Hadrons are viewed as being composed of quarks, known as mesons (which are intermediate mass particles made up of a quark–antiquark pair) or as baryons (which are massive particles made up of three quarks in the standard model). This class of particles includes the proton and neutron. Other baryons are the lambda, sigma, xi, and omega particles.

Recent experimental evidence shows the existence of five-quark combinations, which are being called pentaquarks.

There are six varieties of quarks (and their antimatter counterparts), whimsically named *up*, *down*, *charm*, *strange*, *top*, and *bottom*. The property with which the names of the quarks are associated is known as *flavor*. (Who says scientists don't have a sense of humor?) The fractional elementary charges of the six quarks are shown in the table:

Flavor	Charge
Up (*u*)	+2/3 *e*
Down (*d*)	−1/3 *e*
Charm (*c*)	+2/3 *e*
Strange (*s*)	−1/3 *e*
Top (*t*)	+2/3 *e*
Bottom (*b*)	−1/3 *e*

According to the standard model scheme, the proton has the structure *uud* and the neutron has the structure *udd*. Using the table, we can calculate the charges on the proton and neutron:

$$\text{Proton} = uud = [(+2/3\ e) + (+2/3\ e) + (-1/3\ e)] = e$$
$$\text{Neutron} = udd = [(+2/3\ e) + (-1/3\ e) + (-1/3\ e)] = 0$$

It is important to note that in the above results and in all combinations of quarks that form mesons and baryons, the sum of the fractional charges always adds up to a whole integer value multiple of *e*, the elementary charge that Robert Millikan found on an electron (see Chapter 8). This is in complete agreement with all well-known scientific observations.

The lepton has a mass less than that of a proton. Electrons and neutrinos are classified as leptons. The chart below, which also appears on the Physics Reference Tables, summarizes the properties of each of the six members of the lepton family.

Leptons

electron e –1e	muon μ –1e	tau τ –1e
electron neutrino ν_e 0	muon neutrino ν_μ 0	tau neutrino ν_τ 0

Note: For each particle there is a corresponding antiparticle with a charge opposite that of its associated particle.

Antiparticles are particles that have the identical mass, lifetime, and spin but opposite charge (if charged) and opposite sign magnetic moment. An antiparticle is denoted by a bar over the symbol for the particle. As previously defined in Section 14.8, the positron is the antiparticle to the electron, and it is denoted by the symbol $\bar{e}$. Antimatter is material consisting of atoms that are comprised of antiprotons, antineutrons, and positrons.

The energies needed to reduce protons, neutrons, and other nuclear particles into their constituent quarks are so high that these quarks cannot be isolated as separate particles. Therefore, their existence has been demonstrated only by indirect means. Whether quarks represent the ultimate structure of matter or whether there are even smaller subunits continues to be the subject of research.

Part A and B

1. Neutral atoms always have e
   (1) protons and neutrons
   (2) electrons and neutrons