Chapter 19

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C1

A night view of a nuclear power plant cooling tower in Arkansas.

Since the chemistry of an atom is determined by the number and arrangement of its electrons, the properties of the nucleus are not of primary importance to chemists. In the simplest view, the nucleus provides the positive charge to bind the electrons in atoms and molecules. However, a quick reading of any daily newspaper will show you that the nucleus and its properties have an important impact on our society. This chapter considers those aspects of the nucleus about which everyone should have some knowledge.

Several aspects of the nucleus are immediately impressive: its very small size, its very large density, and the magnitude of the energy that holds it together. The radius of a typical nucleus appears to be about 10^-13 cm. This can be compared to the radius of a typical atom, which is on the order of 10^-8 cm. A visualization will help you appreciate the small size of the nucleus: If the nucleus of the hydrogen atom were the size of a Ping-Pong ball, the electron in the 1s orbital would be, on average, 0.5 kilometer (0.3 mile) away. The density of the nucleus is equally impressive—approximately 1.6 X 10^14 g/cm3. A sphere of nuclear material the size of a Ping-Pong ball would have a mass of 2.5 billion tons! In addition, the energies involved in nuclear processes are typically millions of times larger than those associated with normal chemical reactions. This fact makes nuclear processes very attractive for feeding the voracious energy appetite of our civilization.

Atomos, the Greek root of the word atom, means “indivisible.” It was originally believed that the atom was the ultimate indivisible particle of which all matter was composed. However, as we discussed in Chapter 2, Lord Rutherford showed in 1911 that the atom is not homogeneous, but rather has a dense, positively charged center surrounded by electrons. Subsequently, scientists have learned that the nucleus of the atom can be subdivided into particles called neutrons and protons. In fact, in the past two decades it has become apparent that even the protons and neutrons are composed of smaller particles called quarks.

For most purposes, the nucleus can be regarded as a collection of nucleons (neutrons and protons), and the internal structures of these particles can be ignored. As we discussed in Chapter 2, the number of protons in a particular nucleus is called the atomic number (Z), and the sum of the neutrons and protons is the mass number (A). Atoms that have identical atomic numbers but different mass number values are called isotopes. However, we usually do not use the singular form isotope to refer to a particular member of a group of isotopes. Rather, we use the term nuclide. A nuclide is a unique atom, represented by the symbol

//Image

C2

//Quote

The atomic number Z

is the number of protons in a nucleus; the mass number A is the sum of protons and neutrons in a nucleus.

refers to a group of nuclides with the same atomic number. Each individual atom is properly called a nuclide, The term isotopes

//Heading

19.1 Nuclear Stability and Radioactive Decay

Nuclear stability is the central topic of this chapter and forms the basis for all the important applications related to nuclear processes. Nuclear stability can be considered from both a kinetic and a thermodynamic point of view. Thermodynamic stability, as we will use the term here, refers to the potential energy of a particular nucleus as compared with the sum of the potential energies of its component protons and neutrons. We will use the term kinetic stability to describe the probability that a nucleus will undergo decomposition to form a different nucleus—a process called radioactive decay. We will consider radioactivity in this section.

Many nuclei are radioactive; that is, they decompose, forming another nucleus and producing one or more particles. An example is carbon-14, which decays as follows:

//Chemical Reaction

C3

where 1 0e represents an electron, which is called a beta particle, or β particle, in nuclear terminology. This equation is typical of those representing radioactive decay in that both A and Z must be conserved. That is, the Z values must give the same sum on both sides of the equation (6 = 7 - 1), as must the A values (14 - 14 = 0). Of the approximately 2000 known nuclides, only 279 are stable with respect to radioactive decay. Tin has the largest number of stable isotopes—10. It is instructive to examine how the numbers of neutrons and protons in a nucleus are related to its stability with respect to radioactive decay. Figure 19.1 shows a plot of the positions of the stable nuclei as a function of the number of protons (Z) and the number of neutrons (A - Z). The stable nuclides are said to reside in the zone of stability. The following are some important observations concerning radioactive decay:

• All nuclides with 84 or more protons are unstable with respect to radioactive decay.

• Light nuclides are stable when Z equals A - Z, that is, when the neutron/proton ratio is 1. However, for heavier elements the neutron/proton ratio required for stability is greater than 1 and increases with Z.

//Image

C4

Figure 19.1 The zone of stability. The red dots indicate the nuclides that do not undergo radioactive decay. Note that as the number of protons in a nuclide increases, the neutron/proton ratio required for stability also increases.

//Table

C5

• Certain combinations of protons and neutrons seem to confer special stability. For example, nuclides with even numbers of protons and neutrons are more often stable than those with odd numbers, as shown by the data in Table 19.1.

• There are also certain speciﬁc numbers of protons or neutrons that produce especially stable nuclides. These magic numbers are 2, 8, 20, 28, 50, 82, and 126. This behavior parallels that for atoms in which certain numbers of electrons (2, 10, 18, 36, 54, and 86) produce special chemical stability (the noble gases).

//Sub Heading

Types of Radioactive Decay

Radioactive nuclei can undergo decomposition in various ways. These decay processes fall into two categories: those that involve a change in the mass number of the decaying nucleus and those that do not. We will consider the former type of process ﬁrst.

An alpha particle, or α particle, is a helium nucleus (4 2He). Alpha-particle production is a very common mode of decay for heavy radioactive nuclides. For example, 238 92U, the predominant (99.3%) isotope of natural uranium, decays by -particle production:

//Chemical Reaction

C6

//Quote

Another decay process in which the mass number of the decaying nucleus changes is spontaneous ﬁssion, the splitting of a heavy nuclide into two lighter nuclides with similar mass numbers. Although this process occurs at an extremely slow rate for most nuclides, it is important in some cases, such as for 254 98Cf, where spontaneous ﬁssion is the predominant mode of decay.

The most common decay process in which the mass number of the decaying nucleus remains constant is β-particle production. For example, the thorium-234 nuclide produces a β particle and is converted to protactinium-234:

//Chemical Reaction

C7

The β particle is assigned the mass number 0, since its mass is tiny compared with that of a proton or neutron. Because the value of Z is -1 for the β particle, the atomic number for the new nuclide is greater by 1 than for the original nuclide. Thus the net effect of -particle production is to change a neutron to a proton. We therefore expect nuclides that lie above the zone of stability (those nuclides whose neutron/proton ratios are too high) to be β-particle producers. It should be pointed out that although the particle is an electron, the emitting nucleus does not contain electrons. As we shall see later in this chapter, a given quantity ofenergy (which is best regarded as a form of matter) can become a particle (another form of matter) under certain circumstances. The unstable nuclide creates an electron as it releases energy in the decay process. The electron thus results from the decay process rather than being present before the decay occurs. Think of this as somewhat like talking: Words are not stored inside us but are formed as we speak. Later in this chapter we will discuss in more detail this very interesting phenomenon where matter in the form of particles and matter in the form of energy can interchange.

A gamma ray, or γ ray, refers to a high-energy photon. Frequently, γ-ray production accompanies nuclear decays and particle reactions, such as in the α-particle decay of 238 92U:

//Chemical Reaction

C8

where two γ rays of different energies are produced in addition to the γ particle. The emission of rays is one way a nucleus with excess energy (in an excited nuclear state) can relax to its ground state. Positron production occurs for nuclides that are below the zone of stability (those nuclides whose neutron/proton ratios are too small). The positron is a particle with the same mass as the electron but opposite charge. An example of a nuclide that decays by positron production is sodium-22:

//Chemical Reaction

C9

Note that the net effect is to change a proton to a neutron, causing the product nuclide to have a higher neutron/proton ratio than the original nuclide. Besides being oppositely charged, the positron shows an even more fundamental difference from the electron: It is the antiparticle of the electron. When a positron collides with an electron, the particulate matter is changed to electromagnetic radiation in the form of high-energy photons:

//Chemical Reaction

C10

This process, which is characteristic of matter–antimatter collisions, is called annihilation and is another example of the interchange of the forms of matter. Electron capture is a process in which one of the inner-orbital electrons is captured by the nucleus, as illustrated by the process

//Chemical Reaction

C11

This reaction would have been of great interest to the alchemists, but unfortunately it does not occur at a rate that would make it a practical means for changing mercury to gold. Gamma rays are always produced along with electron capture to release excess energy. The various types of radioactive decay are summarized in Table 19.2.

//Table

C12

//Example

Example 19.1 Nuclear Equations I

Write balanced equations for each of the following processes.

a. 11 6C produces a positron.

b. 214 83Bi produces a β particle.

c. 237 93Np produces an α particle.

//Solution

Solution

Solution a. We must ﬁnd the product nuclide represented by A ZX in the following equation:

//Chemical Reaction

C13

We can ﬁnd the identity of A ZX by recognizing that the total of the Z and A values must be the same on both sides of the equation. Thus for X, Z must be 6 - 1 = 5 and A must be 11 - 0 = 11. Therefore, A ZX is 11 5B. (The fact that Z is 5 tells us that the nuclide is boron.) Thus the balanced equation is

//Chemical Reaction

C14

b. Knowing that a particle is represented by 1 0e and that Z and A are conserved, we can write

//Chemical Reaction

C15

so A ZX must be 214 84Po.

c. Since an β particle is represented by 4 2He, the balanced equation must be

//Chemical Reaction

C16

//Example

Example 19.2

//Image

C17

//Solution

Solution

a. Since A does not change and Z decreases by 1, the missing particle must be an electron:

//Chemical Reaction

C18

This is an example of electron capture.

b. To conserve Z and A, the missing particle must be a positron:

//Chemical Reaction

C19

Thus potassium-38 decays by positron production.

//Image

C20

The decay series from 238 92U to 206 82Pb. Each nuclide in the series except 206 82Pb is radioactive, and the successive transformations (shown by the arrows) continue until 238 82Pb is ﬁnally formed. The horizontal red arrows indicate α-particle production (Z increases by 1 and A is unchanged). The diagonal blue arrows signify α-particle production (both A and Z decrease).

Often a radioactive nucleus cannot reach a stable state through a single decay process. In such a case, a decay series occurs until a stable nuclide is formed. A well-known example is the decay series that starts with 238 92U and ends with 206 82Pb, as shown in Fig. 19.2. Similar series exist for 235 92U:

//Image

C21

//Heading

19.2 The Kinetics of Radioactive Decay

In a sample containing radioactive nuclides of a given type, each nuclide has a certain probability of undergoing decay. Suppose that a sample of 1000 atoms of a certain nuclide produces 10 decay events per hour. This means that over the span of an hour, 1 out of every 100 nuclides will decay. Given that this probability of decay is characteristic for this type of nuclide, we could predict that a 2000-atom sample would give 20 decay events per hour. Thus, for radioactive nuclides, the rate of decay, which is the negative of the change in the number of nuclides per unit time

//Image

C22

This is the rate law for a ﬁrst-order process, as we saw in Chapter 12. As shown in Section 12.4, the integrated ﬁrst-order rate law is

//Image

C23

where N0 represents the original number of nuclides (at t = 0) and N represents the number remaining at time t

//Sub-Heading

Half Life

The half-life (t1/2) of a radioactive sample is deﬁned as the time required for the number of nuclides to reach half the original value (N0/2). We can use this deﬁnition in connection with the integrated ﬁrst-order rate law (as we did in Section 12.4) to produce the following expression for t1/2:

//Image

C24

Thus, if the half-life of a radioactive nuclide is known, the rate constant can be easily calculated, and vice versa.

//Image

C25

The image of a bone scan of a normal chest (posterior view). Radioactive technetium-99m is injected into the patient and is then concentrated in bones, allowing a physician to look for abnormalities such as might be caused by cancer.

//Example

Example 19.3 Kinetics of Nuclear Decay I

Technetium-99m is used to form pictures of internal organs in the body and is often used to assess heart damage. The m for this nuclide indicates an excited nuclear state that decays to the ground state by gamma emission. The rate constant for decay of 43 99mTc is known to be 1.16 x 10^-1/h. What is the half-life of this nuclide?

//Solution

Solution

The half-life can be calculated from the expression

//Image

C26

Thus it will take 5.98 h for a given sample of technetium-99m to decrease to half the original number of nuclides.

As we saw in Section 12.4, the half-life for a ﬁrst-order process is constant. This is shown for the -particle decay of strontium-90 in Fig. 19.3; it takes 28.9 years for each halving of the amount of 90 38Sr. Contamination of the environment with 90 38Sr poses serious health hazards because of the similar chemistry of strontium and calcium (both are in Group 2A). Strontium-90 in grass and hay is incorporated into cow’s milk along with calcium and is then passed on to humans, where it lodges in the bones. Because of its relatively long half-life, it persists for years in humans, causing radiation damage that may lead to cancer.

//Quote

The harmful effects of radiation will be discussed in Section 19.7

//Image

C27

Figure 19.3 The decay of a 10.0-g sample of strontium-90 over time. Note that the half-life is a constant 28.9 years.

//Example

Example 19.4 Kinetics of Nuclear Decay II

The half-life of molybdenum-99 is 66.0 h. How much of a 1.000-mg sample of 99 42Mo is left after 330 h?

//Solution

Solution

The easiest way to solve this problem is to recognize that 330 h represents ﬁve half-lives for 99 42Mo:

//Image

C28

We can sketch the change that occurs, as is shown in Fig. 19.4. Thus, after 330 h, 0.031 mg 99 42Mo remains

The half-lives of radioactive nuclides vary over a tremendous range. For example,

144 60Nd has a half-life of 2.3 x 10^15 years, while 214 84Po has a half-life of 2 x 10^-4 second. To give you some perspective on this, the half-lives of the nuclides in the 238 92U decay series are given in Table 19.3.

//Image

C29

Figure 19.4 The change in the amount of 99 42Mo with time (t1/2 = 66 h).

//Table

C30

//Heading

19.3 Nuclear Transformations

In 1919 Lord Rutherford observed the ﬁrst nuclear transformation, the change of one element into another. He found that by bombarding 14 7N with particles, the nuclide 17 8O could be produced:

//Chemical Reaction

C31

Fourteen years later, Irene Curie and her husband Frederick Joliot observed a similar transformation from aluminum to phosphorus:

//Chemical Reaction

C32

where 1 0n represents a neutron. Over the years, many other nuclear transformations have been achieved, mostly using particle accelerators, which, as the name reveals, are devices used to give particles very high velocities. Because of the electrostatic repulsion between the target nucleus and a positive ion, accelerators are needed when positive ions are used as bombarding particles. The particle, accelerated to a very high velocity, can overcome the repulsion and penetrate the target nucleus, thus effecting the transformation. A schematic diagram of one type of particle accelerator, the cyclotron, is shown in Fig. 19.5. The ion is introduced at the center of the cyclotron and is accelerated in an expanding spiral path by use of alternating electric ﬁelds in the presence of a magnetic ﬁeld. The linear accelerator.

//Image

C33

Figure 19.5 A schematic diagram of a cyclotron. The ion is introduced in the center and is pulled back and forth between the hollow D-shaped electrodes by constant reversals of the electric ﬁeld. Magnets above and below these electrodes produce a spiral path that expands as the particle velocity increases. When the particle has sufﬁcient speed, it exits the accelerator and is directed at the target nucleus. illustrated in Fig. 19.6 employs changing electric ﬁelds to achieve high velocities on a linear pathway. In addition to positive ions, neutrons are often employed as bombarding particles to effect nuclear transformations. Because neutrons are uncharged and thus not repelled electrostatically by a target nucleus, they are readily absorbed by many nuclei, leading to new nuclides. The most common source of neutrons for this purpose is a ﬁssion reactor (see Section 19.6). By using neutron and positive-ion bombardment, scientists have been able to extend the periodic table. Prior to 1940, the heaviest known element was uranium (Z = 92), but in 1940, neptunium (Z = 93) was produced by neutron bombardment of 238 92U. The process initially gives 239 92U, which decays to 239 93Np by β-particle production:

//Image

C34

Figure 19.6 Schematic diagram of a linear accelerator, which uses a changing electric ﬁeld to accelerate a positive ion along a linear path. As the ion leaves the source, the odd-numbered tubes are negatively charged, and the even-numbered tubes are positively charged. The positive ion is thus attracted into tube 1. As the ion leaves tube 1, the tube polarities are reversed. Now tube 1 is positive, repelling the positive ion, and tube 2 is negative, attracting the positive ion. This process continues, eventually producing high particle velocity.

//Table

C35

In the years since 1940, the elements with atomic numbers greater than 92, called the transuranium elements,\* have been synthesized. Many of these elements have very short half-lives, as shown in Table 19.4. As a result, only a few atoms of some have ever been formed. This, of course, makes the chemical characterization of these elements extremely difﬁcult.

//Heading

19.4 Detection and Uses of Radioactivity

Although various instruments measure radioactivity levels, the most familiar of them is the Geiger–Müller counter, or Geiger counter (see Fig. 19.7). This instrument takes advantage of the fact that the high-energy particles from radioactive decay processes produce ions when they travel through matter. The probe of the Geiger counter is ﬁlled with argon gas, which can be ionized by a rapidly moving particle. This reaction is demonstrated by the equation:

//Quote

Geiger counters are often called survey meters in the industry.

//Image

C36

Figure 19.7 A schematic representation of a Geiger–Müller counter. The high-energy radioactive particle enters the window and ionizes argon atoms along its path. The resulting ions and electrons produce a momentary current pulse, which is ampliﬁed and counted.

Normally, a sample of argon gas will not conduct a current when an electrical potential is applied. However, the formation of ions and electrons produced by the passage of the high-energy particle allows a momentary current to ﬂow. Electronic devices detect this current ﬂow, and the number of these events can be counted. Thus the decay rate of the radioactive sample can be determined.

Another instrument often used to detect levels of radioactivity is a scintillation counter, which takes advantage of the fact that certain substances, such as zinc sulﬁde, give off light when they are struck by high-energy radiation. A photocell senses the ﬂashes of light that occur as the radiation strikes and thus measures the number of decay events per unit of time.

//Sub-Heading

Dating by Radioactivity

Archaeologists, geologists, and others involved in reconstructing the ancient history of the earth rely heavily on radioactivity to provide accurate dates for artifacts and rocks. A method that has been very important for dating ancient articles made from wood or cloth is radiocarbon dating, or carbon-14 dating, a technique originated in the 1940s by Willard Libby, an American chemist who received a Nobel Prize for his efforts in this ﬁeld.

Radiocarbon dating is based on the radioactivity of the nuclide 14 6C, which decays via β-particle production

//Chemical Reaction

C37

//Image

C38

Brigham Young researcher Scott Woodward taking a bone sample for carbon-14 dating at an archaeological site in Egypt.

//Quote

Radioactive nuclides are often called radionuclides. Carbon dating is based on the radionuclide 14 6C.

The 14 6C/12 6C ratio is the basis for carbon14 dating.

Thus carbon-14 is continuously produced by this process, and it continuously decomposes through β-particle production. Over the years, the rates for these two processes have become equal, and like a participant in a chemical reaction at equilibrium, the amount of 14 6C that is present in the atmosphere remains approximately constant. Carbon-14 can be used to date wood and cloth artifacts because the 14 6C, along with the other carbon isotopes in the atmosphere, reacts with oxygen to form carbon dioxide. A living plant consumes carbon dioxide in the photosynthesis process and incorporates the carbon, including 14 6C, into its molecules. As long as the plant lives, the 14 6C/12 6C ratio in its molecules remains the same as in the atmosphere because of the continuous uptake of carbon. However, as soon as a tree is cut to make a wooden bowl or a ﬂax plant is harvested to make linen, the 14 6C/12 6C ratio begins to decrease because of the radioactive decay of 14 6C (the 12 6C nuclide is stable). Since the half-life of 14 6C is 5730 years, a wooden bowl found in an archaeological dig showing a 14 6C/12 6C ratio that is half that found in currently living trees is approximately 5730 years old. This reasoning assumes that the current 14 6C/12 6C ratio is the same as that found in ancient times. Dendrochronologists, scientists who date trees from annual growth rings, have used data collected from long-lived species of trees, such as bristlecone pines and sequoias, to show that the 14 6C content of the atmosphere has changed signiﬁcantly over the ages. These data have been used to derive correction factors that allow very accurate dates to be determined from the observed 14 6C/12 6C ratio in an artifact, especially for artifacts 10,000 years old or younger. Recent measurements of uranium/thorium ratios in ancient coral indicate that dates in the 20,000- to 30,000-year range may have errors as large as 3000 years. As a result, efforts are now being made to recalibrate the 14 6C dates over this period.

//Example

Example 19.5

14C Dating

The remnants of an ancient ﬁre in a cave in Africa showed a 14 6C decay rate of 3.1 counts per minute per gram of carbon. Assuming that the decay rate of 14 6C in freshly cut wood (corrected for changes in the 14 6C content of the atmosphere) is 13.6 counts per minute per gram of carbon, calculate the age of the remnants. The half-life of 14 6C is 5730 years.

//Solution

Solution

The key to solving this problem is to realize that the decay rates given are directly proportional to the number of 14 6C nuclides present. Radioactive decay follows ﬁrst-order kinetics:

//Image

C39

One drawback of radiocarbon dating is that a fairly large piece of the object (from a half to several grams) must be burned to form carbon dioxide, which is then analyzed for radioactivity. Another method for counting 14 6C nuclides avoids destruction of a signiﬁcant portion of a valuable artifact. This technique, requiring only about 10^-3 g, uses a mass spectrometer (see Chapter 3), in which the carbon atoms are ionized and accelerated through a magnetic ﬁeld that deﬂects their path. Because of their different masses, the various ions are deﬂected by different amounts and can be counted separately. This allows a very accurate determination of the 14 6C/12 6C ratio in the sample. In their attempts to establish the geologic history of the earth, geologists have made extensive use of radioactivity. For example, since 238 92U decays to the stable 206 82Pb nuclide, the ratio of 206 82Pb to 238 92U in a rock can, under favorable circumstances, be used to estimate the age of the rock. The radioactive nuclide 176 71Lu, which decays to 176 72Hf, has a halflife of 37 billion years (only 186 nuclides out of 10 trillion decay each year!). Thus this nuclide can be used to date very old rocks. With this technique, scientists have estimated that the earth’s crust formed 4.3 billion years ago.

//Example

Example 19.6 Dating by Radioactivity

A rock containing 238 92U and 206 82Pb was examined to determine its approximate age. Analysis showed the ratio of 206 82Pb atoms to 238 92U atoms to be 0.115. Assuming that no lead was originally present, that all the 206 82Pb formed over the years has remained in the rock, and that the number of nuclides in intermediate stages of decay between 238 92U and 206 82Pb is negligible, calculate the age of the rock. The half-life of 238 92U is 4.5 x10^9 years.

//Solution

Solution

//Image

C40

//Quote

Because the half-life of 238 92U is very long compared with those of the other members of the decay series (see Table 19.3) to reach 206 82Pb, the number of nuclides present in intermediate stages of decay is negligible.That is, once a 238 92U nuclide starts to decay, it reaches 206 82Pb relatively fast

//Sub-Heading

Medical Applications of Radioactivity

Although the rapid advances of the medical sciences in recent decades are due to many causes, one of the most important has been the discovery and use of radiotracers, radioactive nuclides that can be introduced into organisms in food or drugs and whose pathways can be traced by monitoring their radioactivity. For example, the incorporation of nuclides such as 14 6C and 32 15P into nutrients has produced important information about metabolic pathways.

Iodine-131 has proved very useful in the diagnosis and treatment of illnesses of the thyroid gland. Patients drink a solution containing small amounts of Na131I, and the uptake of the iodine by the thyroid gland is monitored with a scanner (see Fig. 19.8). Thallium-201 can be used to assess the damage to the heart muscle in a person who has suffered a heart attack, because thallium is concentrated in healthy muscle tissue. Technetium-99m is also taken up by normal heart tissue and is used for damage assessment in a similar way.

//Image

C41

Figure 19.8 After consumption of Na131l, the patient’s thyroid is scanned for radioactivity levels to determine the efﬁciency of iodine absorption. (left) A normal thyroid. (right) An enlarged thyroid.

//Image

C42

//Table

C 43

Radiotracers provide sensitive and noninvasive methods for learning about biologic systems, for detection of disease, for monitoring the action and effectiveness of drugs, and for early detection of pregnancy, and their usefulness should continue to grow. Some useful radiotracers are listed in Table 19.5.

//Heading

19.5 Thermodynamic Stability of the Nucleus

We can determine the thermodynamic stability of a nucleus by calculating the change in potential energy that would occur if that nucleus were formed from its constituent protons and neutrons. For example, let’s consider the hypothetical process of forming a16 8O nucleus from eight neutrons and eight protons:

//Image

C 44

//Image

C45

Thus 0.1366 g of mass would be lost if 1 mole of oxygen-16 were formed from protons and neutrons. What is the reason for this difference in mass, and how can this information be used to calculate the energy change that accompanies this process? The answers to these questions can be found in the work of Albert Einstein. As we discussed in Section 7.2, Einstein’s theory of relativity showed that energy should be considered a form of matter. His famous equation

//Image

C46

where c is the speed of light, gives the relationship between a quantity of energy and its mass. When a system gains or loses energy, it also gains or loses a quantity of mass, given by E/c^2. Thus the mass of a nucleus is less than that of its component nucleons because the process is so exothermic. Einstein’s equation in the form

//Image

C47

where ∆m is the change in mass, or the mass defect, can be used to calculate ∆E for the hypothetical formation of a nucleus from its component nucleons.

//Quote

Energy is a form of matter.

The energy changes associated with normal chemical reactions are small enough that the corresponding mass changes are not detectable.

//Example

Example 19.7 Nuclear Binding Energy I

Calculate the change in energy if 1 mol 16 8O nuclei was formed from neutrons and protons.

// Solution

Solution

We have already calculated that 0.1366 g of mass would be lost in the hypothetical process of assembling 1 mol 16 8O nuclei from the component nucleons. We can calculate the change in energy for this process from

//Image

C48

The negative sign for the ∆E value indicates that the process is exothermic. Energy, and thus mass, is lost from the system.

The energy changes observed for nuclear processes are extremely large compared with those observed for chemical and physical changes. Thus nuclear processes constitute a potentially valuable energy resource.

The thermodynamic stability of a particular nucleus is normally represented as energy released per nucleon. To illustrate how this quantity is obtained, we will continue to

consider 16 8O. First, we calculate ∆E per nucleus by dividing the molar value from Example 19.7 by Avogadro’s number:

//Image

C49

This means that 7.98 MeV of energy per nucleon would be released if 16 8O were formed from neutrons and protons. The energy required to decompose this nucleus into its components has the same numeric value but a positive sign (since energy is required). This is called the binding energy per nucleon for 16 8O. The values of the binding energy per nucleon for the various nuclides are shown in Fig. 19.9. Note that the most stable nuclei (those requiring the largest energy per nucleon to decompose the nucleus) occur at the top of the curve. The most stable nucleus known is 56 26Fe, which has a binding energy per nucleon of 8.79 MeV

//Example

Example Nuclear Binding Energy II

Calculate the binding energy per nucleon for the 4 2He nucleus (atomic masses: 4 2He = 4.0026 amu; 1 1H = 1.0078 amu).

//Image

C50

Figure 19.9 The binding energy per nucleon as a function of mass number. The most stable nuclei are at the top of the curve. The most stable nucleus is 56 26Fe.

Solution

//Solution

//Image

C51

//Quote

Since atomic masses include the masses of the electrons, to obtain the mass of a given atomic nucleus from its atomic mass, we must subtract the mass of the electrons.

//Heading

19.6 Nuclear Fission and Nuclear Fusion

The graph shown in Fig. 19.9 has very important implications for the use of nuclear processes as sources of energy. Recall that energy is released, that is, E is negative, when a process goes from a less stable to a more stable state. The higher a nuclide is on the

//Image

C52

Figure 19.10 Both ﬁssion and fusion produce more stable nuclides and are thus exothermic.

curve, the more stable it is. This means that two types of nuclear processes will be exothermic (see Fig. 19.10):

1. Combining two light nuclei to form a heavier, more stable nucleus. This process is called fusion.

2. Splitting a heavy nucleus into two nuclei with smaller mass numbers. This process is called ﬁssion.

Because of the large binding energies involved in holding the nucleus together, both these processes involve energy changes more than a million times larger than those associated with chemical reactions.

//Sub Heading

Nuclear Fission

Nuclear ﬁssion was discovered in the late 1930s when 235 92U nuclides bombarded with neutrons were observed to split into two lighter elements:

//Chemical Reaction

C53

This process, shown schematically in Fig. 19.11, releases 3.5 x 10^-11 J of energy per event, which translates to 2.1 x 10^13 J per mole of 235 92U. Compare this ﬁgure with that for the combustion of methane, which releases only 8.0 X 105 J of energy per mole. The ﬁssion of 235 92U produces about 26 million times more energy than the combustion of methane.

//Image

C54

Figure 19.11 On capturing a neutron, the 235 92U nucleus undergoes ﬁssion to produce two lighter nuclides, free neutrons (typically three), and a large amount of energy

//Image

C55

Figure 19.12 Representation of a ﬁssion process in which each event produces two neutrons, which can go on to split other nuclei, leading to a self-sustaining chain reaction.

The process shown in Fig. 19.11 is only one of the many ﬁssion reactions that 235 92U can undergo. Another is

//Chemical Reaction

C56

In fact, over 200 different isotopes of 35 different elements have been observed among the ﬁssion products of 235 92U

. In addition to the product nuclides, neutrons are produced in the ﬁssion reactions of 235 92U. This makes it possible to have a self-sustaining ﬁssion process—a chain reaction (see Fig. 19.12). For the ﬁssion process to be self-sustaining, at least one neutron from each ﬁssion event must go on to split another nucleus. If, on average, less than one neutron causes another ﬁssion event, the process dies out and the reaction is said to be subcritical.

If exactly one neutron from each ﬁssion event causes another ﬁssion event, the process sustains itself at the same level and is said to be critical. If more than one neutron from each ﬁssion event causes another ﬁssion event, the process rapidly escalates and the heat buildup causes a violent explosion. This situation is described as supercritical. To achieve the critical state, a certain mass of ﬁssionable material, called the critical mass, is needed. If the sample is too small, too many neutrons escape before they have a chance to cause a ﬁssion event, and the process stops. This is illustrated in Fig. 19.13.

During World War II, an intense research effort called the Manhattan Project was carried out by the United States to build a bomb based on the principles of nuclear ﬁssion. This program produced the ﬁssion bombs that were used with devastating effects on the cities of Hiroshima and Nagasaki in 1945. Basically, a ﬁssion bomb operates by suddenly combining subcritical masses of ﬁssionable material to form a supercritical mass, thereby producing an explosion of incredible intensity.

//Image

C57

Figure 19.13 If the mass of ﬁssionable material is too small, most of the neutrons escape before causing another ﬁssion event, and the process dies out

//Chemical Connections

//Sub-Heading

Future Nuclear Power

Energy—a crucial commodity in today’s world—will become even more important as the pace of world development increases. Because the energy content of the universe is constant, the challenge of energy is not its quantity but rather its quality. We must ﬁnd economical and environmentally friendly ways to change the energy available in the universe to forms useful to humanity. This process always involves tradeoffs.

Currently, about 65% of the world’s energy consumption involves combustion of fossil fuels (coal, 39%; natural gas, 19%; oil, 7%). The use of these fuels causes signiﬁcant pollution and contributes huge amounts of greenhouse gases (mostly CO2) to the atmosphere.

One of the most abundant sources of energy is the energy that binds the atomic nucleus together. We can derive useful energy by assembling small nuclei (fusion) or splitting large nuclei (ﬁssion). Although fusion reactors are being studied, a practical fusion reactor appears to be decades away. By contrast, ﬁssion reactors have been used since the 1950s. In fact, the production of electricity via ﬁssion reactors is widespread. At present, more than 400 nuclear reactors operate in 31 countries, producing over 355 billionwatts of electrical power (see accompanying table). More than 30 reactors are currently under construction, and at least 100 more are in the planning stages. The 103 reactors currently operating in the United States produce almost 100 billion watts of electricity—about 20% of the country’s electrical demands.

//Image

C58

Forecasts indicate that the United States will need an additional 355 billion watts of generating capacity in the next 20 years. Where will this energy come from? A signiﬁcant amount will be derived from coal-ﬁred power plants with their inherent environmental problems.

Another potential source of power is solar energy. It should be an excellent pollution-free energy source, but signiﬁcant technical problems remain to be solved before it sees widespread use.

Wind power is also being developed but promises to make only a limited contribution to overall energy use. The most important power source is nuclear energy. To provide all of the 355 billion watts from nuclear energy would require hundreds of new reactors. However, nuclear power generation is very controversial because of safety, waste disposal, and cost issues. On the other hand, nuclear energy produces no greenhouse gases, has a much lower volume of waste products than the combustion of fossil fuels, has an almost unlimited supply of fuel, and has an excellent safety record. Research is now under way to improve existing reactor designs and to ﬁnd new types of reactors that will be safer, more efﬁcient, and generate much less waste by ﬁnding ways to reprocess the reactor fuel.

Actually, the United States has demonstrated an ability to deal successfully with the long-term storage of nuclear wastes. The Waste Isolation Pilot Plant (WIPP) in New Mexico has been receiving nuclear wastes since 1999 with no accidents in either transporting or storing the wastes. WIPP uses tunnels carved into the salt beds of an ancient ocean. Once a repository room becomes full, the salt will collapse around the waste, encapsulating it forever.

There is no doubt that nuclear energy will be important to the United States and to the world. An excellent source of information about all aspects of nuclear energy use is the book Power to Save the World—The Truth About Nuclear Energy, by Gwyneth Cravens (Alfred A. Knopf, New York, 2007). This book is a thorough but very readable treatment of the subject.

//Sub Heading

Nuclear Reactors

Because of the tremendous energies involved, it seemed desirable to develop the ﬁssion process as an energy source to produce electricity. To accomplish this, reactors were designed in which controlled ﬁssion can occur. The resulting energy is used to heat water to produce steam to run turbine generators, in much the same way that a coal-burning power plant generates energy. A schematic diagram of a nuclear power plant is shown in Fig. 19.14.

In the reactor core, shown in Fig. 19.15, uranium that has been enriched to approximately 3% 235 92U (natural uranium contains only 0.7% 235 92U) is housed in cylinders. A moderator surrounds the cylinders to slow down the neutrons so that the uranium fuel can capture them more efﬁciently. Control rods, composed of substances that absorb neutrons, are used to regulate the power level of the reactor. The reactor is designed so that should a malfunction occur, the control rods are automatically inserted into the core to stop the reaction. A liquid (usually water) is circulated through the core to extract the heat generated by the energy of ﬁssion; the energy can then be passed on via a heat exchanger to water in the turbine system.

//Image

C59

Figure 19.14 A schematic diagram of a nuclear power plant.

//Image

C60

Figure 19.15 A schematic of a reactor core. The position of the control rods determines the level of energy production by regulating the amount of ﬁssion taking place.

Although the concentration of 235 92U in the fuel elements is not great enough to allow a supercritical mass to develop in the core, a failure of the cooling system can lead to temperatures high enough to melt the core. As a result, the building housing the core must be designed to contain the core even if meltdown occurs. A great deal of controversy now exists about the efﬁciency of the safety systems in nuclear power plants. Accidents such as the one at the Three Mile Island facility in Pennsylvania in 1979 and in Chernobyl,\* Ukraine, in 1986 have led to questions about the wisdom of continuing to build ﬁssionbased power plants.

//Image

C61

//Sub Heading

Breeder Reactors

One potential problem facing the nuclear power industry is the supply of 235 92U. Some scientists have suggested that we have nearly depleted those uranium deposits rich enough in 235 92U to make production of ﬁssionable fuel economically feasible. Because of this possibility, breeder reactors have been developed, in which ﬁssionable fuel is actually produced while the reactor runs. In the breeder reactors now being studied, the major component of natural uranium, nonﬁssionable 238 92U, is changed to ﬁssionable 239 94Pu. The reaction involves absorption of a neutron, followed by production of two β particles:

//Image

C62

As the reactor runs and 235 92U is split, some of the excess neutrons are absorbed by 238 92U to produce 239 94Pu. The 239 94Pu is then separated out and used to fuel another reactor. Such a reactor thus “breeds” nuclear fuel as it operates. Although breeder reactors are now used in France, the United States is proceeding slowly with their development because of their controversial nature. One problem involves the hazards in handling plutonium, which ﬂames on contact with air and is very toxic.

//Sub Heading

Fusion

Large quantities of energy are also produced by the fusion of two light nuclei. In fact, stars produce their energy through nuclear fusion. Our sun, which presently consists of 73% hydrogen, 26% helium, and 1% other elements, gives off vast quantities of energy from the fusion of protons to form helium:

//Image

C63

Intense research is under way to develop a feasible fusion process because of the ready availability of many light nuclides (deuterium, 2 1H, in seawater, for example) that can serve as fuel in fusion reactors. The major stumbling block is that high temperatures are required to initiate fusion. The forces that bind nucleons together to form a nucleus are effective only at very small distances (-10^-13 cm). Thus, for two protons to bind together and thereby release energy, they must get very close together. But protons, because they are identically charged, repel each other electrostatically. This means that to get

two protons (or two deuterons) close enough to bind together (the nuclear binding force is not electrostatic), they must be “shot” at each other at speeds high enough to overcome the electrostatic repulsion.

The electrostatic repulsion forces between two 2 1H nuclei are so great that a temperature of 4 X 10^7 K is required to give them velocities large enough to cause them to collide with sufﬁcient energy that the nuclear forces can bind the particles together and thus release the binding energy. This situation is represented in Fig. 19.16.

Currently, scientists are studying two types of systems to produce the extremely high temperatures required: high-powered lasers and heating by electric currents. At present, many technical problems remain to be solved, and it is not clear which method will prove more useful or when fusion might become a practical energy source. However, there is still hope that fusion will be a major energy source sometime in the future.

//Image

C64

Figure 19.16 A plot of energy versus the separation distance for two 2 1H nuclei. The nuclei must have sufﬁcient velocities to get over the electrostatic repulsion “hill” and get close enough for the nuclear binding forces to become effective, thus “fusing” the particles into a new nucleus and releasing large quantities of energy. The binding force is at least 100 times the electrostatic repulsion

//Heading

19.7 Effects of Radiation

Everyone knows that being hit by a train is very serious. The problem is the energy transfer involved. In fact, any source of energy is potentially harmful to organisms. Energy transferred to cells can break chemical bonds and cause malfunctioning of the cell systems. This fact is behind the concern about the ozone layer in the earth’s upper atmosphere, which screens out high-energy ultraviolet radiation from the sun. Radioactive elements, which are sources of high-energy particles, are also potentially hazardous, although the effects are usually quite subtle. The reason for the subtlety of radiation damage is that even though high-energy particles are involved, the quantity of energy actually deposited in tissues per event is quite small. However, the resulting damage is no less real, although the effects may not be apparent for years.

//Chemical connection

Nuclear Physics: An Introduction

Nuclear physics is concerned with the fundamental nature of matter. The central focuses of this area of study are the relationship between a quantity of energy and its mass, given by E = mc^2, and the fact that matter can be converted from one form (energy) to another (particulate) in particle accelerators. Collisions between high-speed particles have produced a dazzling array of new particles—hundreds of them. These events can best be interpreted as conversions of kinetic energy into particles. For example, a collision of sufﬁcient energy between a proton and a neutron can produce four particles: two protons, one antiproton, and a neutron:

//Chemical Reaction

C 65

where 1 -1H is the symbol for an antiproton, which has the same mass as a proton but the opposite charge. This process is a little like throwing one baseball at a very high speed into another and having the energy of the collision converted into two additional baseballs.

The results of such accelerator experiments have led scientists to postulate the existence of three types of forces important in the nucleus: the strong force, the weak force, and the electromagnetic force. Along with the gravitational force, these forces are thought to account for all types of interactions found in matter. These forces are believed to be generated by the exchange of particles between the interacting pieces of matter. For example, gravitational forces are thought to be carried by particles called gravitons. The electromagnetic force (the classical electrostatic force between charged particles) is assumed to be exerted through the exchange of photons. The strong force, not chargerelated and effective only at very short distances (=10^-13 cm), is postulated to involve the exchange of particles called gluons.

The weak force is 100 times weaker than the strong force and seems to be exerted through the exchange of two types of large particles, the W (has a mass 70 times the proton mass) and the Z (has a mass 90 times the proton mass).

The particles discovered have been classiﬁed into several categories. Three of the most important classes are as follows:

1. Hadrons are particles that respond to the strong force and have internal structure.

2. Leptons are particles that do not respond to the strong force and have no internal structure.

3. Quarks are particles with no internal structure that are thought to be the fundamental constituents of hadrons. Neutrons and protons are hadrons that are thought to be composed of three quarks each.

elements, which are sources of high-energy particles, are also potentially hazardous, although the effects are usually quite subtle. The reason for the subtlety of radiation damage is that even though high-energy particles are involved, the quantity of energy actually deposited in tissues per event is quite small. However, the resulting damage is no less real, although the effects may not be apparent for years. Radiation damage to organisms can be classiﬁed as somatic or genetic damage. Somatic damage is damage to the organism itself, resulting in sickness or death. The effects may appear almost immediately if a massive dose of radiation is received; for smaller doses, damage may appear years later, usually in the form of cancer. Genetic damage is damage to the genetic machinery, which produces malfunctions in the offspring of the organism. The biologic effects of a particular source of radiation depend on several factors:

1. The energy of the radiation. The higher the energy content of the radiation, the more damage it can cause. Radiation doses are measured in rads (which is short for radiation absorbed dose), where 1 rad corresponds to 10^-2 J of energy deposited per kilogram of tissue.

2. The penetrating ability of the radiation. The particles and rays produced in radioactive processes vary in their abilities to penetrate human tissue: γ rays are highly penetrating, β particles can penetrate approximately 1 cm, and α particles are stopped by the skin.

//Quote

The ozone layer is discussed in Section 20.11.

The world of particle physics appears mysterious and complicated. For example, particle physicists have discovered new properties of matter they call “color,” “charm,” and “strangeness” and have postulated conservation laws involving these properties. This area of science is extremely important because it should help us to understand the interactions of matter in a more elegant and uniﬁed way. For example, the classiﬁcation of force into four categories is probably necessary only because we do not understand the true nature of forces. All forces may be special cases of a single, all-pervading force ﬁeld that governs all of nature. In fact, Einstein spent the last 30 years of his life looking for a way to unify the gravitational and electromagnetic forces— without success. Physicists may now be on the verge of accomplishing what Einstein failed to do.

Although the practical aspects of the work in nuclear physics are not yet totally apparent, a more fundamental understanding of the way nature operates could lead to presently undreamed-of devices for energy production and communication, which could revolutionize our lives.

//Image

C66

3. The ionizing ability of the radiation. Extraction of electrons from biomolecules to form ions is particularly detrimental to their functions. The ionizing ability of radiation varies dramatically. For example, rays penetrate very deeply but cause only occasional ionization. On the other hand, particles, although not very penetrating, are very effective at causing ionization and produce a dense trail of damage. Thus ingestion of an -particle producer, such as plutonium, is particularly damaging.

4. The chemical properties of the radiation source. When a radioactive nuclide is ingested into the body, its effectiveness in causing damage depends on its residence time. For example, 85 36Kr and 90 38Sr are both β-particle producers. However, since krypton is chemically inert, it passes through the body quickly and does not have much time to do damage. Strontium, being chemically similar to calcium, can collect in bones, where it may cause leukemia and bone cancer.

Because of the differences in the behavior of the particles and rays produced by radioactive decay, both the energy dose of the radiation and its effectiveness in causing biologic damage must be taken into account. The rem (which is short for roentgen equivalent for man) is deﬁned as follows:

Number of rems = (number of rads) X RBE

where RBE represents the relative effectiveness of the radiation in causing biologic damage.

//Table

C67

Table 19.6 shows the physical effects of short-term exposure to various doses of radiation, and Table 19.7 gives the sources and amounts of radiation exposure for a typical person in the United States. Note that natural sources contribute about twice as much as human activities to the total exposure.

However, although the nuclear industry contributes only a small percentage of the total exposure, the major controversy associated with nuclear power plants is the potential for radiation hazards. These arise mainly from two sources: accidents allowing the release of radioactive materials and improper disposal of the radioactive products in spent fuel elements. The radioactive products of the ﬁssion of 235 92U, although only a small percentage of the total products, have half-lives of several hundred years and remain dangerous for a long time. Various schemes have been advanced for the disposal of these wastes. The one that seems to hold the most promise is the incorporation of the wastes into ceramic blocks and the burial of these blocks in geologically stable formations. At present, however, no disposal method has been accepted, and nuclear wastes continue to accumulate in temporary storage facilities.

Even if a satisfactory method for permanent disposal of nuclear wastes is found, there will continue to be concern about the effects of exposure to low levels of radiation. Exposure is inevitable from natural sources such as cosmic rays and radioactive minerals, and many people are also exposed to low levels of radiation from reactors, radioactive tracers, or diagnostic X rays. Currently, we have little reliable information on the longterm effects of low-level exposure to radiation.

Two models of radiation damage, illustrated in Fig. 19.17, have been proposed: the linear model and the threshold model. The linear model postulates that damage from radiation is proportional to the dose, even at low levels of exposure. Thus any exposure is dangerous. The threshold model, on the other hand, assumes that no signiﬁcant damage occurs below a certain exposure, called the threshold exposure. Note that if the linear model is correct, radiation exposure should be limited to a bare minimum (ideally at the natural levels). If the threshold model is correct, a certain level of radiation exposure beyond natural levels can be tolerated. Most scientists feel that since there is little evidence available to evaluate these models, it is safest to assume that the linear hypothesis is correct and to minimize radiation exposure.

//Table

C68

//Image

C69

Figure 19.17 The two models for radiation damage. In the linear model, even a small dosage causes a proportional risk. In the threshold model, risk begins only after a certain dosage

//key Terms

Neutron

proton

nucleon

atomic number

mass number

isotopes

nuclide

Section 19.1

thermodynamic stability

kinetic stability

radioactive decay

beta (β) particle

zone of stability

alpha (α) particle

α-particle production

spontaneous ﬁssion

α -particle production

gamma (γ) ray

positron production

electron capture

decay series

Section 19.2

rate of decay

half-life

Section 19.3

nuclear transformation

particle accelerator

cyclotron

linear accelerator

transuranium elements

Section 19.4

Geiger–Müller counter (Geiger counter)

scintillation counter

radiocarbon dating (carbon-14 dating)

radiotracers

Section 19.5

mass defect

binding energy

Section 19.6

Fusion

ﬁssion

chain reaction

subcritical reaction

critical reaction

supercritical reaction

critical mass reactor

core moderator

control rods

breeder reactor

Section 19.7

somatic damage

genetic damage

rad

rem

//For Review

Radioactivity

Certain nuclei decay spontaneously into more stable nuclei

Types of radioactive decay:

• α-particle (4 2He) production

• β-particle (1 0e) production

• Positron (0 1e) production

• γ rays are usually produced in a radioactive decay event

A decay series involves several radioactive decays to ﬁnally reach a stable nuclide

Radioactive decay follows ﬁrst-order kinetics

• Half-life of a radioactive sample: the time required for half of the nuclides to decay

The transuranium elements (those beyond uranium in the periodic table) can be synthesized by particle bombardment of uranium or heavier elements

Radiocarbon dating employs the 14 6C/12 6C ratio in an object to establish its date of origin.

Thermodynamic stability of a nucleus

Compares the mass of a nucleus to the sum of the masses of its component nucleons.

When a system gains or loses energy, it also gains or loses mass as described by the relationship E = mc^2

The difference between the sum of the masses of the component nucleons and the actual mass of a nucleus (called the mass defect) can be used to calculate the nuclear binding energy

Nuclear energy production

Fusion: the process of combining two light nuclei to form a heavier, more stable nucleus

Fission: the process of splitting a heavy nucleus into two lighter, more stable nuclei

• Current nuclear power reactors employ controlled ﬁssion to produce energy

Radiation damage

Radiation can cause direct (somatic) damage to a living organism or genetic damage to the organism’s offspring

The biologic effects of radiation depend on the energy, the penetrating ability, the ionizing ability of the radiation, and the chemical properties of the nuclide producing the radiation

//Review Question

1. Deﬁne or illustrate the following terms:

a. thermodynamic stability

b. kinetic stability

c. radioactive decay

d. beta-particle production

e. alpha-particle production

f. positron production

g. electron capture

h. gamma-ray emissions In radioactive decay processes, A and Z are conserved. What does this mean?

2. Figure 19.1 illustrates the zone of stability. What is the zone of stability? Stable light nuclides have about equal numbers of neutrons and protons. What happensto the neutron-to-proton ratio for stable nuclides as the number of protons increases? Nuclides that are not already in the zone of stability undergo radioactive processes to get to the zone of stability. If a nuclide has too many neutrons, which process(es) can the nuclide undergo to become more stable? Answer the same question for a nuclide having too many protons.

3. All radioactive decay processes follow ﬁrst-order kinetics. What does this mean? What happens to the rate of radioactive decay as the number of nuclides is halved? Write the ﬁrst-order rate law and the integrated ﬁrst-order rate law. Deﬁne the terms in each equation. What is the half-life equation for radioactive decay processes? How does the half-life depend on how many nuclides are present? Are the halflife and rate constant k directly related or inversely related?

4. What is a nuclear transformation? How do you balance nuclear transformation reactions? Particle accelerators are used to perform nuclear transformations. What is a particle accelerator?

5. What is a Geiger counter and how does it work? What is a scintillation counter and how does it work? Radiotracers are used in the medical sciences to learn about metabolic pathways. What are radiotracers? Explain why 14C and 32P radioactive nuclides would be very helpful in learning about metabolic pathways. Why is I-131 useful for diagnosis of diseases of the thyroid? How could you use a radioactive nuclide to demonstrate that chemical equilibrium is a dynamic process?

6. Explain the theory behind carbon-14 dating. What assumptions must be made and what problems arise when using carbon-14 dating?

The decay of uranium-238 to lead-206 is also used to estimate the age of objects. Speciﬁcally, 206Pb-to-238U ratios allow dating of rocks. Why is the 238U decay to 206Pb useful for dating rocks but useless for dating objects 10,000 years old or younger? Similarly, why is carbon-14 dating useful for dating objects 10,000 years old or younger but useless for dating rocks?

7. Deﬁne mass defect and binding energy. How do you determine the mass defect for a nuclide? How do you convert the mass defect into the binding energy for a nuclide? Iron-56 has the largest binding energy per nucleon among all known nuclides. Is this good or bad for iron-56? Explain.

8. Deﬁne ﬁssion and fusion. How does the energy associated with ﬁssion or fusion processes compare to the energy changes associated with chemical reactions? Fusion processes are more likely to occur for lighter elements, whereas ﬁssion processes are more likely to occur for heavier elements. Why? (Hint: Reference Fig. 19.10.) The major stumbling block for turning fusion reactions into a feasible source of power is the high temperature required to initiate a fusion reaction. Why are elevated temperatures necessary to initiate fusion reactions but not ﬁssion reactions?

9. The ﬁssion of U-235 is used exclusively in nuclear power plants located in the United States. There are many different ﬁssion reactions of U-235, but all the ﬁssion reactions are self-sustaining chain reactions. Explain. Differentiate between the terms critical, subcritical, and supercritical. What is the critical mass? How does a nuclear power plant produce electricity? What are the purposes of the moderator and the control rods in a ﬁssion reactor? What are some problems associated with nuclear reactors? What are breeder reactors? What are some problems associated with breeder reactors?

10. The biological effects of a particular source of radiation depend on several factors. List some of these factors. Even though 85Kr and 90Sr are both betaparticle emitters, the dangers associated with the decay of 90Sr are much greater than those linked to 85Kr. Why? Although gamma rays are far more penetrating than alpha particles, the latter are more likely to cause damage to an organism. Why? Which type of radiation is more effective at promoting the ionization of biomolecules?

//Question

1. When nuclei undergo nuclear transformations, γ rays of characteristic frequencies are observed. How does this fact, along with other information in the chapter on nuclear stability, suggest that a quantum mechanical model may apply to the nucleus?

2. There is a trend in the United States toward using coal-ﬁred power plants to generate electricity rather than building new nuclear ﬁssion power plants. Is the use of coal-ﬁred power plants without risk? Make a list of the risks to society from the use of each type of power plant.

3. Which type of radioactive decay has the net effect of changing a neutron into a proton? Which type of decay has the net effect of turning a proton into a neutron? 4. What is annihilation in terms of nuclear processes?

5. What are transuranium elements and how are they synthesized?

6. Scientists have estimated that the earth’s crust was formed 4.3 billion years ago. The radioactive nuclide 176Lu, which decays to 176Hf, was used to estimate this age. The half-life of 176Lu is 37 billion years. How are ratios of 176Lu to 176Hf utilized to date very old rocks?

7. Why are the observed energy changes for nuclear processes so much larger than the energy changes for chemical and physical processes?

8. Natural uranium is mostly nonﬁssionable 238U; it contains only about 0.7% of ﬁssionable 235U. For uranium to be useful as a nuclear fuel, the relative amount of 235U must be increased to about 3%. This is accomplished through a gas diffusion process. In the diffusion process, natural uranium reacts with ﬂuorine to form a mixture of 238UF6(g) and 235UF6(g). The ﬂuoride mixture is then enriched through a multistage diffusion process to produce a 3% 235U nuclear fuel. The diffusion process utilizes Graham’s law of effusion (see Chapter 5, Section 5.7). Explain how Graham’s law of effusion allows natural uranium to be enriched by the gaseous diffusion process.

9. Much of the research on controlled fusion focuses on the problem of how to contain the reacting material. Magnetic ﬁelds appear to be the most promising mode of containment. Why is containment such a problem? Why must one resort to magnetic ﬁelds for containment?

10. A recent study concluded that any amount of radiation exposure can cause biological damage. Explain the differences between the two models of radiation damage, the linear model and the threshold model.

// Exercises

Radioactive Decay and Nuclear Transformations

11. Write an equation describing the radioactive decay of each of the following nuclides. (The particle produced is shown in parentheses, except for electron capture, where an electron is a reactant.)

a. 3 1H (β)

b. 8 3Li (β followed by α)

c. 7 4Be (electron capture)

d. 8 5B (positron)

12. In each of the following radioactive decay processes, supply the missing particle.

//Image

C70

13. Write an equation describing the radioactive decay of each of the following nuclides. (The particle produced is shown in parentheses, except for electron capture, where an electron is a reactant.)

a. 68Ga (electron capture)

b. 62Cu (positron)

c. 212Fr (α)

d. 129Sb β

14. In each of the following radioactive decay processes, supply the missing particle

//Image

C71

15. Uranium-235 undergoes a series of β-particle and β-particle productions to end up as lead-207. How many α particles and β particles are produced in the complete decay series?

16. The radioactive isotope 247Bk decays by a series of α-particle and β-particle productions, taking 247Bk through many transformations to end up as 207Pb. In the complete decay series, how many α particles and β particles are produced?

One type of commercial smoke detector contains a minute amount of radioactive americium-241 (241Am), which decays by α-particle production. The α particles ionize molecules in the air, allowing it to conduct an electric current. When smoke particles enter, the conductivity of the air is changed and the alarm buzzes.

a. Write the equation for the decay of 241 95Am by α-particle production.

b. The complete decay of 241Am involves successively α, α, β, α, α, , α, α, α, β, β, and β production. What is the ﬁnal stable nucleus produced in this decay series? c. Identify the 11 intermediate nuclides.

18. Thorium-232 is known to undergo a progressive decay series until it reaches stability at lead-208. For each step of the series indicated in the table below, indicate which nuclear particle is emitted

//Image

C72

19. There are four stable isotopes of iron with mass numbers 54, 56, 57, and 58. There are also two radioactive isotopes: iron-53 and iron59. Predict modes of decay for these two isotopes. (See Table 19.2.)

20. The only stable isotope of ﬂuorine is ﬂuorine-19. Predict possible modes of decay for ﬂuorine-21, ﬂuorine-18, and ﬂuorine-17.

21. In 1994 it was proposed (and eventually accepted) that element 106 be named seaborgium, Sg, in honor of Glenn T. Seaborg, discoverer of the transuranium elements.

a. 263Sg was produced by the bombardment of 249Cf with a beam of 18O nuclei. Complete and balance an equation for this reaction.

b. 263Sg decays by α emission. What is the other product resulting from the α decay of 263Sg?

22. Many elements have been synthesized by bombarding relatively heavy atoms with high-energy particles in particle accelerators. Complete the following nuclear reactions, which have been used to synthesize elements.

//Image

C73

Kinetics of Radioactive Decay

23. The rate constant for a certain radioactive nuclide is 1.0 x 10^-3 h^-1. What is the half-life of this nuclide?

24. Americium-241 is widely used in smoke detectors. The radiation released by this element ionizes particles that are then detected by a charged-particle collector. The half-life of 241Am is 433 years, and it decays by emitting alpha particles. How many alpha particles are emitted each second by a 5.00-g sample of 241Am?

25. Krypton consists of several radioactive isotopes, some of which are listed in the following table

//Image

C74

Which of these isotopes is most stable and which isotope is “hottest”? How long does it take for 87.5% of each isotope to decay?

26. Radioactive copper-64 decays with a half-life of 12.8 days.

a. What is the value of k in s^-1?

b. A sample contains 28.0 mg 64Cu. How many decay events will be produced in the ﬁrst second? Assume the atomic mass of 64Cu is 64.0.

c. A chemist obtains a fresh sample of 64Cu and measures its radioactivity. She then determines that to do an experiment, the radioactivity cannot fall below 25% of the initial measured value. How long does she have to do the experiment?

27. A chemist wishing to do an experiment requiring 47Ca^2+ (halflife = 4.5 days) needs 5.0 g of the nuclide. What mass of 47CaCO3 must be ordered if it takes 48 h for delivery from the supplier? Assume that the atomic mass of 47Ca is 47.0.

28. The curie (Ci) is a commonly used unit for measuring nuclear radioactivity: 1 curie of radiation is equal to 3.7 x 10^10 decay events per second (the number of decay events from 1 g radium in 1 s). a. What mass of Na238SO4 has an activity of 10.0 mCi? Sulfur38 has an atomic mass of 38.0 and a half-life of 2.87 h. b. How long does it take for 99.99% of a sample of sulfur-38 to decay?

29. The ﬁrst atomic explosion was detonated in the desert north of Alamogordo, New Mexico, on July 16, 1945. What fraction of the strontium-90 (t1/2 = 28.9 years) originally produced by that explosion still remains as of July 16, 2009?

30. Iodine-131 is used in the diagnosis and treatment of thyroid disease and has a half-life of 8.0 days. If a patient with thyroid disease consumes a sample of Na131I containing 10. µg 131I, how long will it take for the amount of 131I to decrease to 1/100 of the original amount?

31. The Br-82 nucleus has a half-life of 1.0 x 103 min. If you wanted 1.0 g Br-82 and the delivery time was 3.0 days, what mass of NaBr should you order (assuming all of the Br in the NaBr was Br-82)?

32. Fresh rainwater or surface water contains enough tritium (3 1H) to show 5.5 decay events per minute per 100. g water. Tritium has a half-life of 12.3 years. You are asked to check a vintage wine that is claimed to have been produced in 1946. How many decay events per minute should you expect to observe in 100. g of that wine?

33. A living plant contains approximately the same fraction of carbon14 as in atmospheric carbon dioxide. Assuming that the observed rate of decay of carbon-14 from a living plant is 13.6 counts per minute per gram of carbon, how many counts per minute per gram of carbon will be measured from a 15,000-year-old sample? Will radiocarbon dating work well for small samples of 10 mg or less? (For 14C, t1/2 = 5730 years.)

34. Assume a constant 14C/12C ratio of 13.6 counts per minute per gram of living matter. A sample of a petriﬁed tree was found to give 1.2 counts per minute per gram. How old is the tree? (For 14C, t1/2 = 5730 years.)

35. A rock contains 0.688 mg 206Pb for every 1.000 mg 238U present. Assuming that no lead was originally present, that all the 206Pb formed over the years has remained in the rock, and that the number of nuclides in intermediate stages of decay between 238U and 206Pb is negligible, calculate the age of the rock. (For 238U, t1/2 x 4.5 = 109 years.)

36. The mass ratios of 40Ar to 40K also can be used to date geologic materials. Potassium-40 decays by two processes:

//Image

C75

a. Why are 40Ar/40K ratios used to date materials rather than 40Ca40K ratios?

b. What assumptions must be made using this technique?

c. A sedimentary rock has an 40Ar/40K ratio of 0.95. Calculate the age of the rock.

d. How will the measured age of a rock compare to the actual age if some 40Ar escaped from the sample?

37. The sun radiates 3.9 x 10^23 J of energy into space every second. What is the rate at which mass is lost from the sun?

38. The earth receives 1.8 X 10^14 kJ/s of solar energy. What mass of solar material is converted to energy over a 24-h period to provide the daily amount of solar energy to the earth? What mass of coal would have to be burned to provide the same amount of energy? (Coal releases 32 kJ of energy per gram when burned.)

39. Many transuranium elements, such as plutonium-232, have very short half-lives. (For 232Pu, the half-life is 36 minutes.) However, some, like protactinium-231 (half-life 3.34 x 10^4 years), have relatively long half-lives. Use the masses given in the following table to calculate the change in energy when 1 mol 232Pu nuclei and 1 mol 231Pa nuclei are each formed from their respective number of protons and neutrons.

//Image

C76

(Since the masses of 232Pu and 231Pa are atomic masses, they each include the mass of the electrons present. The mass of the nucleus will be the atomic mass minus the mass of the electrons.)

40. The most stable nucleus in terms of binding energy per nucleon is 56Fe. If the atomic mass of 56Fe is 55.9349 amu, calculate the binding energy per nucleon for 56Fe.

41. Calculate the binding energy in J/nucleon for carbon-12 (atomic mass 12.0000) and uranium-235 (atomic mass 235.0439). The atomic mass of 1 1H is 1.00782 amu and the mass of a neutron is 1.00866 amu. The most stable nucleus known is 56Fe (see Exercise 40). Would the binding energy per nucleon for 56Fe be larger or smaller than that of 12C or 235U? Explain.

42. Calculate the binding energy per nucleon for 2 1H and 3 1H. The atomic masses are 2 1H, 2.01410, and 3 1H, 3.01605.

43. The mass defect for a Li-6 nucleus is 0.03434 g/mol. Calculate the atomic mass of Li-6.

44. The binding energy per nucleon for Mg-27 is 1.326 x 10^12 J/nucleon. Calculate the atomic mass of Mg-27.

45. Calculate the amount of energy released per gram of hydrogen nuclei reacted for the following reaction. The atomic masses are 1 1H, 1.00782 amu; 2 1H, 2.01410 amu; and an electron, 5.4858 x 10^-4 amu. (Hint: Think carefully about how to account for the electron mass.)

//Image

C77

Calculate the energy released per 4 2He nucleus produced and per mole of 4 2He produced. The atomic masses are 2 1H, 2.01410; 3 1H, 3.01605; and 4 2He, 4.00260. The masses of the electron and neutron are 5.4858 X 10^-4 amu and 1.00866 amu, respectively.

Detection, Uses, and Health Effects of Radiation

47. The typical response of a Geiger–Müller tube is shown below. Explain the shape of this curve.

//Image

C78

48. When using a Geiger–Müller counter to measure radioactivity, it is necessary to maintain the same geometrical orientation between the sample and the Geiger–Müller tube to compare different measurements. Why?

49. Consider the following reaction to produce methyl acetate:

//Image

C79

When this reaction is carried out with CH3OH containing oxygen18, the water produced does not contain oxygen-18. Explain

. 50. A chemist studied the reaction mechanism for the reaction

//Chemical Reaction

C80

what distribution of 18O would you expect in the NO2? Assume that N is the central atom in NO3, assume only N16O18O2 forms, and assume stoichiometric amounts of reactants are combined.

51. U-235 undergoes many different ﬁssion reactions. For one such reaction, when U-235 is struck with a neutron, Ce-144 and Sr90 are produced along with some neutrons and electrons. How many neutrons and β-particles are produced in this ﬁssion reaction?

52. Breeder reactors are used to convert the nonﬁssionable nuclide 238 92U to a ﬁssionable product. Neutron capture of the 238 92U is followed by two successive beta decays. What is the ﬁnal ﬁssionable product?

53. Which do you think would be the greater health hazard: the release of a radioactive nuclide of Sr or a radioactive nuclide of Xe into the environment? Assume the amount of radioactivity is the same in each case. Explain your answer on the basis of the chemical properties of Sr and Xe. Why are the chemical properties of a radioactive substance important in assessing its potential health hazards?

54. Consider the following information:

//Image

C81

Connecting to Biochemistry

55. Write balanced equations for each of the processes described below.

a. Chromium-51, which targets the spleen and is used as a tracer in studies of red blood cells, decays by electron capture.

b. Iodine-131, used to treat hyperactive thyroid glands, decays by producing a β particle.

c. Phosphorus-32, which accumulates in the liver, decays by βparticle production.

56. Each of the following isotopes has been used medically for the purpose indicated. Suggest reasons why the particular element might have been chosen for this purpose. a. cobalt-57, for study of the body’s use of vitamin B12 b. calcium-47, for study of bone metabolism c. iron-59, for study of red blood cell function

57. Technetium-99 has been used as a radiographic agent in bone scans (99 43Tc is absorbed by bones). If 99 43Tc has a half-life of 6.0 hours, what fraction of an administered dose of 100. µg 99 43Tc remains in a patient’s body after 2.0 days?

58. The mass percent of carbon in a typical human is 18%, and the mass percent of 14C in natural carbon is 1.6 x 10^-10%. Assuming a 180-lb person, how many decay events per second occur in this person due exclusively to the β-particle decay of 14C (for 14C, t1/2 = 5730 years)?

59. Phosphorus-32 is a commonly used radioactive nuclide in biochemical research, particularly in studies of nucleic acids. The half-life of phosphorus-32 is 14.3 days. What mass of phosphorus32 is left from an original sample of 175 mg Na332PO4 after 35.0 days? Assume the atomic mass of 32P is 32.0. 60.

A 0.20-mL sample of a solution containing 3 1H that produces 3.7 x 103 cps is injected into the bloodstream of an animal. After allowing circulatory equilibrium to be established, a 0.20-mL sample of blood is found to have an activity of 20. cps. Calculate the blood volume of the animal.

61. Photosynthesis in plants can be represented by the following overall reaction:

//Chemical Reaction

C82

Algae grown in water containing some 18O (in H218O) evolve oxygen gas with the same isotopic composition as the oxygen in the water. When algae growing in water containing only 16O were

furnished carbon dioxide containing 18O, no 18O was found to be evolved from the oxygen gas produced. What conclusions about photosynthesis can be drawn from these experiments?

62. Strontium-90 and radon-222 both pose serious health risks. 90Sr decays by β-particle production and has a relatively long half-life (28.9 years). Radon-222 decays by β-particle production and has a relatively short half-life (3.82 days). Explain why each decay process poses health risks.

// Additional Exercises

63. Predict whether each of the following nuclides is stable or unstable (radioactive). If the nuclide is unstable, predict the type of radioactivity you would expect it to exhibit.

//Image

C83

64. At a ﬂea market, you’ve found a very interesting painting done in the style of Rembrandt’s “dark period” (1642–1672). You suspect that you really do not have a genuine Rembrandt, but you take it to the local university for testing. Living wood shows a carbon14 activity of 15.3 counts per minute per gram. Your painting showed a carbon-14 activity of 15.1 counts per minute per gram. Could it be a genuine Rembrandt?

65. Deﬁne “third-life” in a similar way to “half-life” and determine the “third-life” for a nuclide that has a half-life of 31.4 years.

66. A proposed system for storing nuclear wastes involves storing the radioactive material in caves or deep mine shafts. One of the most toxic nuclides that must be disposed of is plutonium-239, which is produced in breeder reactors and has a half-life of 24,100 years. A suitable storage place must be geologically stable long enough for the activity of plutonium-239 to decrease to 0.1% of its original value. How long is this for plutonium-239?

67. During World War II, tritium (3H) was a component of ﬂuorescent watch dials and hands. Assume you have such a watch that was made in January 1944. If 17% or more of the original tritium was needed to read the dial in dark places, until what year could you read the time at night? (For 3H, t1/2 x 12.3 yr.)

68. A positron and an electron can annihilate each other on colliding, producing energy as photons:

//Chemical Reaction

C83

Assuming that both µ rays have the same energy, calculate the wavelength of the electromagnetic radiation produced.

69. A small atomic bomb releases energy equivalent to the detonation of 20,000 tons of TNT; a ton of TNT releases 4 X 10^9 J of energy when exploded. Using 2 x 10^13 J/mol as the energy released by ﬁssion of 235U, approximately what mass of 235U undergoes ﬁssion in this atomic bomb?

70. During the research that led to production of the two atomic bombs used against Japan in World War II, different mechanisms for obtaining a supercritical mass of ﬁssionable material were investigated. In one type of bomb, a “gun” shot one piece of ﬁssionable material into a cavity containing another piece of ﬁssionable material. In the second type of bomb, the ﬁssionable material was surrounded with a high explosive that, when detonated, compressed the ﬁssionable material into a smaller volume. Discuss what is meant by critical mass, and explain why the ability to achieve a critical mass is essential to sustaining a nuclear reaction.

71. Using the kinetic molecular theory (Section 5.6), calculate the root mean square velocity and the average kinetic energy of 2 1H nuclei at a temperature of 4 x 10^7 K. (See Exercise 46 for the appropriate mass values.)

72. Consider the following reaction, which can take place in particle accelerators:

Calculate the energy change for this reaction. Is energy released or absorbed? What is a possible source for this energy?

Challenge Problems

73. Naturally occurring uranium is composed mostly of 238U and 235U, with relative abundances of 99.28% and 0.72%, respectively. The half-life for 238U is 4.5 x 10^9 years, and the half-life for 235U is 7.1 x 10^8 years. Assuming that the earth was formed 4.5 billion years ago, calculate the relative abundances of the 238U and 235U isotopes when the earth was formed.

74. The curie (Ci) is a commonly used unit for measuring nuclear radioactivity: 1 curie of radiation is equal to 3.7 x 10^10 decay events per second (the number of decay events from 1 g radium in 1 s). A 1.7-mL sample of water containing tritium was injected into a 150-lb person. The total activity of radiation injected was 86.5 mCi. After some time to allow the tritium activity to equally distribute throughout the body, a sample of blood plasma containing 2.0 mL water at an activity of 3.6 Ci was removed. From these data, calculate the mass percent of water in this 150-lb person.

75. A 0.10-cm3 sample of a solution containing a radioactive nuclide (5.0 x 10^3 counts per minute per milliliter) is injected into a rat. Several minutes later 1.0 cm3 blood is removed. The blood shows 48 counts per minute of radioactivity. Calculate the volume of blood in the rat. What assumptions must be made in performing this calculation?

76. Zirconium is one of the few metals that retains its structural integrity upon exposure to radiation. The fuel rods in most nuclear reactors therefore are often made of zirconium. Answer the following questions about the redox properties of zirconium based on the half-reaction

//Chemical Reaction

C 84

a. Is zirconium metal capable of reducing water to form hydrogen gas at standard conditions?

b. Write a balanced equation for the reduction of water by zirconium.

c. Calculate , ∆G, and K for the reduction of water by zirconium metal.

d. The reduction of water by zirconium occurred during the accidents at Three Mile Island in 1979. The hydrogen produced was successfully vented and no chemical explosion occurred. If 1.00 X 10^3 kg Zr reacts, what mass of H2 is produced? What volume of H2 at 1.0 atm and 1000.C is produced?

e. At Chernobyl in 1986, hydrogen was produced by the reaction of superheated steam with the graphite reactor core

//Chemical Reaction

C85

It was not possible to prevent a chemical explosion at Chernobyl. In light of this, do you think it was a correct decision to vent the hydrogen and other radioactive gases into the atmosphere at Three Mile Island? Explain.

77. In addition to the process described in the text, a second process called the carbon–nitrogen cycle occurs in the sun:

//Image

C86

a. What is the catalyst in this process? b. What nucleons are intermediates? c. How much energy is released per mole of hydrogen nuclei in the overall reaction? (The atomic masses of 1 1H and 4 2He are 1.00782 and 4.00260, respectively.)

78. The most signiﬁcant source of natural radiation is radon-222. 222Rn, a decay product of 238U, is continuously generated in the earth’s crust, allowing gaseous Rn to seep into the basements of buildings. Because 222Rn is an -particle producer with a relatively short half-life of 3.82 days, it can cause biological damage when inhaled. a. How many β particles and β particles are produced when 238U decays to 222Rn? What nuclei are produced when 222Rn decays?

b. Radon is a noble gas so one would expect it to pass through the body quickly. Why is there a concern over inhaling 222Rn?

c. Another problem associated with 222Rn is that the decay of 222Rn produces a more potent β-particle producer (t1/2 x 3.11 min) that is a solid. What is the identity of the solid? Give the balanced equation of this species decaying by -particle production. Why is the solid a more potent -particle producer?

d. The U.S. Environmental Protection Agency (EPA) recommends that 222Rn levels not exceed 4 pCi per liter of air (1 Ci = 1 curie = 3.7 x 10^10 decay events per second; 1 pCi = 1 x 10^-12 Ci). Convert 4.0 pCi per liter of air into concentrations units of 222Rn atoms per liter of air and moles of 222Rn per liter of air.

79. To determine the Ksp value of Hg2I2, a chemist obtained a solid sample of Hg2I2 in which some of the iodine is present as radioactive 131I. The count rate of the Hg2I2 sample is 5.0 x 10^11 counts per minute per mole of I. An excess amount of Hg2I2(s) is placed into some water, and the solid is allowed to come to equilibrium with its respective ions. A 150.0-mL sample of the saturated solution is withdrawn and the radioactivity measured at 33 counts per minute. From this information, calculate the Ksp value for Hg2I2.

//Image

C87

80. Estimate the temperature needed to achieve the fusion of deuterium to make an α particle. The energy required can be

estimated from Coulomb’s law [use the form E = 9.0 x 10^9 (Q1Q2/r), using Q = 1.6 x 10^-19 C for a proton, and r x 2 = 10^-15 m for the helium nucleus; the unit for the proportionality constant in Coloumb’s law is J . m/C^2].

Integrative Problems

81. A recently reported synthesis of the transuranium element bohrium (Bh) involved the bombardment of berkelium-249 with neon-22 to produce bohrium-267. Write a nuclear reaction for this synthesis. The half-life of bohrium-267 is 15.0 seconds. If 199 atoms of bohrium-267 could be synthesized, how much time would elapse before only 11 atoms of bohrium-267 remain? What is the expected electron conﬁguration of elemental bohrium?

82. Radioactive cobalt-60 is used to study defects in vitamin B12 absorption because cobalt is the metallic atom at the center of the vitamin B12 molecule. The nuclear synthesis of this cobalt isotope involves a three-step process. The overall reaction is iron58 reacting with two neutrons to produce cobalt-60 along with the emission of another particle. What particle is emitted in this nuclear synthesis? What is the binding energy in J per nucleon for the cobalt-60 nucleus (atomic masses: 60Co = 59.9338 amu; 1H 1.00782 amu)? What is the de Broglie wavelength of the emitted particle if it has a velocity equal to 0.90c where c is the speed of light?