2

Introduction to radioactivity and radioactive decay

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Learning objectives

- Name the major components of an atom
- Describe the four forces in nature and their relevance to the atom
- Calculate energy, atomic mass, and binding energy for nuclei and electrons
- Use the standard definitions and nomenclature for describing nuclides
- Understand the use and application of decay schemes for radionuclides
- Describe different radioactive emissions and how these emissions can interact with matter
- Calculate a radionuclide's decay rate, decay constant, and the amount of radionuclide remaining at different times during decay
- Discuss the units used, and the importance of the effects of radiation exposure.

The atom

The atom has at its center a positively charged nucleus. Surrounding the nucleus is a cloud of up to 100 negatively charged electrons, which rotate around the nucleus along various energy orbits. Normally, the overall nuclear charge is equal in magnitude, but opposite in sign, to the overall electron charge, leaving the atom electrically neutral. The radius of the nucleus, approximately 0.0001 Å (10^{-13} cm [NB 100 pm = 1 Å]), is only a minute percentage of the volume of the entire atom. The nucleus is composed mainly of nucleons, which are protons and neutrons.

Protons

A proton is a nucleon possessing a positive charge. Its mass, 1.6726×10^{-24} g, is approximately 1836 times that of an orbital electron (http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/funcon.html; http://periodic.lanl.gov/default.htm). The number of protons in the nucleus is referred to as the atomic number (Z).

As will be discussed below, mass can be expressed in terms of atomic mass units (AMU) or in million electronvolts (MeV). A proton has a mass of 1.00728 AMU or 938.27 MeV.

Neutrons

A neutron is a nucleon that carries no charge. Its mass, which is similar to that of a proton, is 1.6749×10^{-24} g (1.00867 AMU or 939.57 MeV) (http://periodic.lanl.gov/default.htm). The total number of neutrons in the nucleus is referred to as the neutron number (N).

Neutrons and protons are held to each other by the strong interaction or nuclear binding force, one of the four fundamental forces in nature. The total number of nucleons (protons plus neutrons) in a nucleus is $Z + N$, and is given the letter A. Although the mass of a nucleus from the periodic table or chart of the nuclides is *not* an integer, it is expressed for our initial purposes as A in the equation $A = Z + N$ (MIRDTrilinear Chart of the Nuclides http://wwwndc.jaea.go.jp/CN04). This discrepancy is caused by the nuclear binding energy, which will be discussed below.

In a given element, the number of protons is equal to the number of electrons, resulting in an overall neutral charge for the atom. The electron configuration determines *chemical* properties of an element. The *nuclear structure* determines the stability and the propensity for radioactive decay of the atom's nucleus.

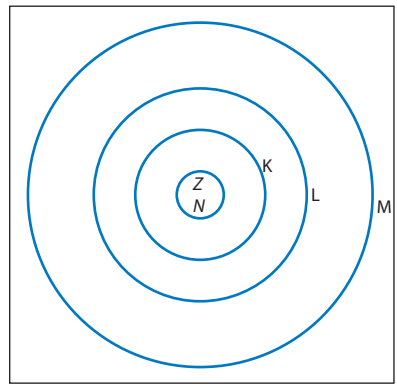

Figure 2.1 An atom with three potential orbitals levels for electrons (*K*, *L*, and *M* shells) surrounding a nucleus containing protons (*Z*) and neutrons (*N*).

Electrons

An electron, with a mass of 9.1094×10^{-28} g (0.000549 AMU, 0.511 MeV), moves in energy levels, not paths, around the nucleus (http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/funcon.html). Lower orbitals (those closer to the nucleus) possess higher kinetic energy and lower potential energy. The electron cloud surrounding an atom has order, in that the electrons orbit at defined energy levels or shells (K, L, M, N, etc.). These shells increase in potential energy the farther from the nucleus they are. If an electron moves from a shell farther from the nucleus to one closer to the nucleus, energy must be released. Conversely, energy must be provided to an electron in order for it to move outward (Figure 2.1).

Again, while nuclear reactions occur in the nucleus, chemical reactions occur with the movement of electrons, and require as little as 10 eV to initiate. This will be important to remember later, when electron binding energy and radiation biology are discussed.

Atomic dimensions

An atom is approximately 10^{-8} cm (approximately 1 Å or 100 pm) in size. As mentioned above, the nucleus is approximately 10^{-13} cm or one fermi (1 F) in size. And, although it contains almost 100% of the atom's mass, its volume is approximately 1/1 000 000 000 000th of the entire volume of the atom. An analogy illustrating the extreme differences in size would be: if an entire atom were a 100 m (round) football field, the nucleus would be approximately 1 cm in size, a proton 1 mm, and an electron would be a mere dot in space.

Atoms follow the basic rules of thermodynamics and physics. Nucleons and electrons tend toward greater stability by giving off kinetic energy to

lower their potential energy. Radioactive decay and the rearrangements of electrons occur in order to make more stable the lower potential energy configurations of the nuclear and electron energy levels, respectively.

Definitions: the nuclear language

- *Radioactive*. The term radioactive means the random and spontaneous disintegration(s) of atomic nuclei that are unstable because of energetically unfavorable nuclear configurations. This involves nuclei moving from higher to lower potential energy states, leading ultimately to stable (non-radioactive) nuclear arrangements. The potential energy is carried away from the nucleus or surrounding electron cloud by various particulate and photon emissions. These radiations take on the forms of α, β^- (negatron, essentially an electron), β^+ (positron), X-rays, and γ photons.
- *Nuclide*. A nuclide is any identifiable atomic species. It has a definite number of protons (Z) and a definite number of neutrons (N).
- *Radionuclide*. This is a radioactive nuclide.
- *Element*. An element is a nuclide with a defined Z (atomic number). For example, if Z is 53, the element is iodine, though the isotope (see below) is not defined.
- *Symbol identification*. A nuclide or radionuclide can be identified by labeling its symbol with three numbers that represent (1) its mass (A), the sum of the number of protons and neutrons; (2) its atomic number (Z), the number of protons; and (3) the number of neutrons (N) (Figure 2.2).
- *Isotopes*. (Derived from the Greek word for 'same place'.) These are nuclides that have the same atomic number (Z) but differ in atomic mass (A). Isotopes also have the same number of electrons and, therefore, possess the same chemical properties. (As stated above, the electron level is where chemical reactions occur.) Some isotopes are stable, others radioactive. For example, ^{14}C and ^{15}C are radioactive isotopes of carbon, while ^{12}C and ^{13}C are not. These differences reflect differing stabilities of the nuclei (Figure 2.3). Generally, elements with lower Z numbers tend to have fewer isotopes than elements with higher Z numbers.

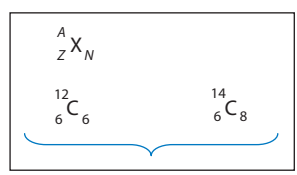

Figure 2.2 Basic nomenclature of a nuclide. *A* is the mass number, the sum of the number of protons and neutrons; *Z* is the atomic number, the number of protons; and *N* is the number of neutrons. The lower part of the figure shows two nuclides of carbon. Note that the number of protons remains the same in both nuclides, while the neutron numbers differ to balance.

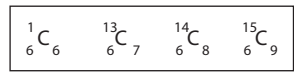

Figure 2.3 Isotopes. Examples here are for carbon, where the number of protons (Z) is 6 for all four isotopes of the same element.

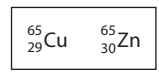

Figure 2.4 Isobars. Examples here are different elements, as it is the atomic number Z that determines the element.

- *Isobars*. These are nuclides that have the same atomic mass (A) but differ from each other in atomic number (Z) and so also in neutron number (N). An example is the pair of isobars copper-65 and zinc-65 (^{65}Cu and ^{65}Zn). These are two different elements, since it is the atomic number that determines the element (Figure 2.4).
- *Isomers*. Nuclides with the same atomic mass (A) and the same atomic number (Z) are known as isomers. The only difference is that one of the isomers is in an excited (metastable) state, and this results in two different energy levels. An example is technetium, where the isomer ^{99m}Tc 'decays' to ^{99}Tc, while emitting a gamma photon (γ) to balance the overall energy. This is written as $^{99m}\text{Tc} \rightarrow {}^{99}\text{Tc} + \gamma$. (Gamma photons will be discussed below.) An isomer is indicated by a lower case 'm' next to the atomic number. Figure 2.5 shows a general form of isomeric decay, or 'isomeric transition.' Isomeric transitions will be discussed in more detail later in the text.
- *Isotones*. Nuclides that have the same number of neutrons (N) but differ in atomic mass (A) are known as isotones; they also differ in the number of protons. An example is the two elements, hydrogen and helium. Both have one neutron, but hydrogen has one proton and helium has two (Figure 2.6).
- *Ions*. Atoms with a net electrical charge, postive or negative, are known as ions. Because ionization is an electronic state, not a nuclear state, ions can be radionuclides or simply nuclides. An ion's net charge is determined by

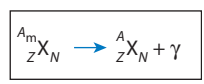

Figure 2.5 Isomers, showing a general form of isomeric decay, or isomeric transition.

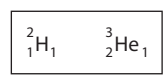

Figure 2.6 Isotones: hydrogen has one proton and helium has two.

the lack, or excess, of one or more electrons from the atom's electron cloud.

Nuclear forces

There are four fundamental forces: gravitational, electromagnetic (coulombic), strong interaction (strong nuclear), and weak interaction (weak nuclear).

- *Gravitational force*. This is principally involved in interactions between large objects. It is too weak at the atomic level to be of much consequence in its effects and is, therefore, not as important at the nuclear level as other forces.
- *Electromagnetic (coulombic) force*. This force, acting mainly outside the nucleus, is exerted on electrically charged particles. An attractive force, it is responsible for holding electrons and protons together in atoms. To understand the comparative strengths of the electromagnetic and gravitational forces, consider the following. The distance between an electron and a proton is roughly 5×10^{-9} cm. The electromagnetic force between the two is approximately 9.2×10^{-3} dynes, whereas the gravitational force is only around 4×10^{-42} dynes. It is obvious that gravitational force is negligible at the atomic level.
- *Strong interaction (strong nuclear) force*. This binds the nucleons together. Although it is much stronger than the electromagnetic force, it does not act outside the nucleus. The strong interaction force is approximately 100 times stronger than the electromagnetic force, approximately 10^{13} times greater than the weak interaction force (described below), and approximately 10^{38} times greater than the gravitational force. It is involved with collisions between protons and other particles. It is strong enough to keep protons proximal in the nucleus and to overcome charge repulsion between them. The strong interaction has no direct effect on electrons since they are extremely small in mass, and at a great distance from the nucleus.
- *Weak interaction (weak nuclear) force*. This is associated with beta and other nuclear decays; it acts over a relatively small range, approximately 10^{-16} cm, which is 1000 times smaller than the diameter of a nucleus. It plays an important role, since it is involved in radioactive decay. The weak interaction force is able to transform neutrons into protons, and protons into neutrons.

So, together, these fundamental forces (mostly the last three) dictate the actions and interactions that occur in the nucleus and the atom's electron cloud. All matter moves toward the configuration that is the most stable. It forfeits kinetic energy in order to move from a point of higher potential

energy to one of lower potential energy. For atoms, this is manifest as the discharge of particles and rays from within the nucleus or from the surrounding electron cloud (http://230nsc1.phy-astr.gsu.edu/hbase/forces/funfor.html; http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/980127c.html). These changes, these movements toward greater stability, are the origin of radioactivity and will, therefore, be thoroughly discussed below. Harnessing these emissions is at the core of nuclear pharmacy, nuclear medicine, and nuclear physics.

Radioactivity calculations

Nuclear pharmacy and nuclear medicine use many units for quantifying such items such as mass, exposure, dose, and radioactivity.

Mass units

The atomic mass unit (AMU) was introduced above. 1 AMU is 1.66053×10^{-24} g, which is understood to be one-twelfth the mass of a ^{12}C atom (Clarke *et al.* 1903; Mattauch 1958; http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/funcon.html). The mass of a ^{12}C atom (six protons, six neutrons, and six electrons) is 1.992×10^{-23} g. The atomic mass unit for ^{12}C is therefore its mass divided by the mass of 1 AMU:

$$\frac{1.992 \times 10^{-23}\ \text{g}}{^{12}\text{C}_{\text{atom}}} \times \frac{1\ \text{AMU}}{1.660 \times 10^{-24}\ \text{g}} = 12.00\ \text{AMU}$$

The periodic table mass for ^{12}C is 12.011 g. The difference between the periodic table (or chart of the nuclides) mass for an atom and its AMU mass is called the **mass defect** (http://periodic.lanl.gov/default.htm; http://wwwndc.jaea.go.jp/CN04/). This difference is where the conversion between energy and mass occurs, and it is accounted for by the energy required to hold the atom together. This energy can be converted to mass, which is the mass defect.

Energy units

Units of energy are often useful, as well. Recall from physics that force equals mass times acceleration ($F = ma$), with one available unit for expression, the dyne. So, force can be measured in **dynes**. A dyne is an unbalanced push or pull, accelerating 1 g at 1 cm/s. The unit used for the dyne is mass multiplied by distance per time squared (g·cm/s^2).

Another useful energy unit is the **electronvolt** (eV; usually seen as MeV, one million electronvolts); 1 MeV = 23,045,000 calories/mol. The electronvolt is not an SI (International System) unit. The electronvolt can be related to

another energy term, the **erg** (the amount of work done by a force of one dyne exerted for a distance of one centimeter [g·cm^2/s^2]), by the equation

$$\text{Work} = \text{force} \times \text{distance} = \text{energy}$$

One erg is equal to 1.6022×10^{-6} MeV. This can then be used to derive the energy equivalent of 1 AMU. Using $E = mc^2$ to express energy, where c (the speed of light) is 2.997925×10^{10} cm/s, the energy of a mass of 1 AMU (or 1.66053×10^{-24} g) can be calculated as

$$E = mc^2$$

$$E = 1 \text{ AMU} \times (2.997925 \times 10^{10} \text{ cm/s})^2$$

As 1 AMU=1.66053×10^{-24} g, then

$$E = [1.66053 \times 10^{-24} \text{ g}] \times (2.997925 \times 10^{10} \text{ cm/s})^2$$

$$E = 1.492 \times 10^{-3} \text{ erg}$$

As 1 erg = 1.6022×10^{-6} MeV, the energy equivalent of 1 AMU

$$E = \frac{1.492 \times 10^{-3} \text{ erg}}{\text{AMU}} \times \frac{1 \text{ MeV}}{1.6022 \times 10^{6} \text{ erg}} = \frac{931.5 \text{ MeV}}{\text{AMU}}$$

Therefore, the mass of 1 AMU has the energy equivalence of 931.5 MeV.

Substituting the value for the mass of ^{12}C into $E = mc^2$ and dividing by 12 provides the values which were described above:

$$E_{\text{proton}} = 938.27 \text{ MeV}$$

$$E_{\text{neutron}} = 939.57 \text{ MeV}$$

$$E_{\text{electron/beta/positron}} = 0.511 \text{ MeV}$$

Parenthetically, conversion of mass to million electronvolts is

$$\left(\frac{1 \text{ AMU}}{1.660 \times 10^{-24} \text{ g}}\right) \times \left(\frac{931.5 \text{ MeV}}{\text{AMU}}\right) = \frac{5.611 \times 10^{26} \text{ MeV}}{\text{g}}$$

Further application at the atomic level involves ergs and electronvolts. A volt is a unit of potential. An electronvolt is a unit of energy. One electronvolt is equal to one electron accelerated to one volt of potential energy, and is equal to 1.6×10^{-12} erg (1 eV = 1.6×10^{-12} erg). Radioactive emissions are usually quantified using the electronvolt: 1000 eV = 1 keV (thousand electronvolts) and 1000 keV = 1 MeV (million electronvolts). The energy or energies at which radioactive emissions occur are characteristic of certain isotopes, and this can be helpful in identifying the isotope of origin.

Units of radioactivity

Important to nuclear pharmacy and nuclear medicine are units of radioactivity. The fundamental unit of radioactivity is the curie (Ci), which is defined as 3.7×10^{10} disintegrations per second (dps). The SI unit for radioactivity is the becquerel (Bq), which is equal to 1 dps. The SI units are metric and technically are the preferred method of quantifying radioactivity. However, the older system, using curies, millicuries, and microcuries is still relatively prevalent in practice: 1 Ci = 1000 mCi (millicuries) and 1 mCi = 1000 μCi (microcuries). Originally the curie was the number of disintegrations of one gram of pure radium per second. In the 1950s, a new radium half-life was found. Now, for any atom

$$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{dps} = 3.7 \times 10^{10}\ \text{Bq}$$

Some helpful conversions are:

$$1\ \text{mCi} = 37\ \text{MBq} = 3.7 \times 10^{7}\ \text{dps} = 3.7 \times 10^{7}\ \text{Bq}$$

$$1\ \mu\text{Ci} = 37\ \text{kBq} = 3.7 \times 10^{4}\ \text{dps} = 3.7 \times 10^{4}\ \text{Bq}$$

$$1\ \text{Bq} = 1\ \text{dps}$$

$$1\ \text{MBq} = 10^{6}\ \text{Bq} = 10^{6}\ \text{dps} = 2.7 \times 10^{-5}\ \text{Ci} = 2.7 \times 10^{-2}\ \text{mCi} = 0.027\ \text{mCi} = 27\ \mu\text{Ci}$$

An element may be radioactive because of instability in its nucleus, and a nucleus will decay only if it is energetically favorable for it to do so, meaning that it will only do so if it leads to greater stability of the atom. Of importance to the stability (or instability) of the nucleus and electrons is the amount of potential energy required to keep nucleons or electrons in place. These energies are their respective **binding energies**.

Binding energy in the nucleus

For nucleons, the binding energy is the difference between the assigned value from the periodic table and the calculated AMU. These values do differ, and this difference represents the binding energy. The binding energy for nucleons is the energy required to keep the nucleons from dissociating.

Calculating the number of protons present in the nuclide multiplied by 1.6726×10^{-24} g/proton plus the number of neutrons present in the nuclide multiplied by 1.6749×10^{-24} g/neutron, and comparing the results with the mass appearing on the chart of the nuclides (a 'periodic table' for all nuclides) will provide a small difference in grams. This can be converted to MeV to determine the binding energy for the nucleus. Further, the total binding energy can be divided by the number of nucleons present for that

isotope, thus providing the binding energy per nucleon. The binding energy for one particle can often be generalized to equal 7.1 MeV. The true range for atomic masses greater than 11 but less than 60 is 7.4–8.8 MeV. For atomic masses less than 11, the binding energy is approximately 7.1 MeV. Using the value for binding energy, the stability or instability of an element can be predicted. The prediction is based on the difference between the calculated value and the periodic table (the assigned or chart of the nuclides) value. If the nuclear binding energy is negative, the nuclide is unstable and capable of undergoing radioactive decay. If the binding energy is positive, the nuclide is stable and unlikely to undergo decay.

The binding energy for $^{4}\mathrm{He} = 2m_{^{1}\mathrm{H}} + 2m_{\mathrm{n}} - m_{^{4}\mathrm{He}}$ where $m_{^{1}\mathrm{H}}$ is the mass of ^{1}H (a proton), m_{n} is the mass of a neutron, and $m_{^{4}\mathrm{He}}$ is the periodic table atomic mass for helium-4 (^{4}He); this is equal to $2(1.0079) + 2(1.00896) - 4.00260 = 0.03054$ AMU. Since 1 AMU = 931.5 MeV, the binding energy for ^{4}He is 28.45 MeV.

So, as stated above, the binding energy for one nucleon is roughly 7.1 MeV. Figure 2.7 shows a plot of binding energy per nucleon versus mass number, and allows more precise estimates of binding energy per nucleon.

The binding energy for atomic masses less than 11 is approximately 7.1 MeV. Therefore, for elements there is a calculable nuclear binding energy. As stated above, the binding energy can be used to determine if an element is stable:

- negative binding energy: decay favorable
- if the binding energy of products is less than the binding energy of the initial nucleus ($\mathrm{BE}_{\mathrm{products}} - \mathrm{BE}_{\mathrm{initial\ nucleus}} =$ negative value), decay is favorable.

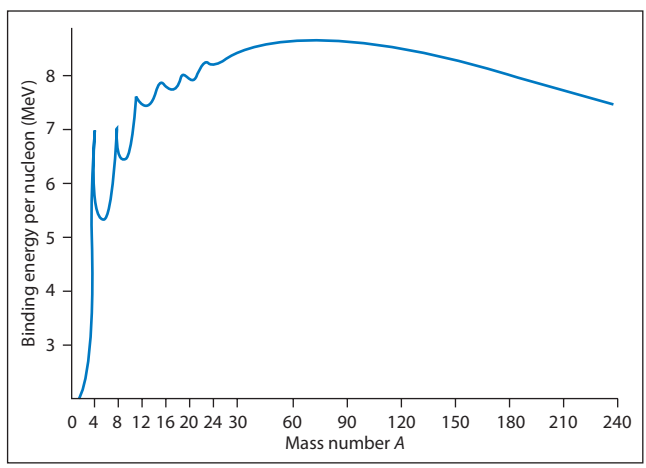

Figure 2.7 The binding energy per nucleon with increasing nuclide atomic mass number.

Because the **half-life** (the time for a radionuclide to decay to half its original value) is inversely proportional to the binding energy, the binding energy can be used to predict the stability of elements. A shorter half-life indicates greater instability.

Binding energy of orbital electrons

The binding energy of orbital electrons is also important because dislodging electrons is another mechanism by which atoms can lose potential energy to become more stable (overall). It is also a mechanism that can lead to other radiations. Like nucleons, electrons possess a binding energy, which keeps them in place in their particular orbital. However, if a collision with a particle or ray from the atom carries enough energy (i.e. energy greater than the electron binding energy), electrons can be dislodged from their orbitals. This results in rearrangements in the orbitals and radioactive emissions, which will be discussed below. The binding energy is the energy required to remove an electron from its orbit around the nucleus and is measured in electronvolts (eV).

It should be kept in mind that chemical reactions occur with electrons and require energy a minimum of only 10 eV per atom. The importance of this will also be discussed below.

Emissions from radioactive decay and their interactions with matter

The stability of an atom is dictated by the arrangement and binding energy of the nucleons. As discussed above, these have a direct bearing on whether a nuclide will be stable or prone to decay. Radionuclides decay by several mechanisms, including fission (splitting of an atom); alpha, beta, positron decay; electron capture; and isomeric transition. Various combinations are also often involved, as multiple decay steps. Of these various decays, all except fission are of consequence to nuclear pharmacy and nuclear medicine. It is often helpful to know not only the tendency of a nuclide to decay, but to be able to predict by which mechanism (or mechanisms) it will tend to decay. One way to predict the most likely decay mechanism is by noting the nuclide's **neutron to proton ratio**.

A graph of the number of neutrons in an atom versus the number of protons has a slope approximately equal to one at the beginning. The elements here, where the neutron to proton ratio is nearly one, tend to be stable. Further up the periodic table, there is a greater proportion of neutrons in nuclides and a higher preponderance of radioactivity. An abundance of neutrons implies increasing instability.

The most stable nuclides contain even numbers of protons and neutrons and, therefore, a neutron to proton ratio of one. Nuclides are less stable when either the number of protons or the number of neutrons is odd. Infrequently, nuclides have odd numbers of *both* protons and neutrons (these are all with

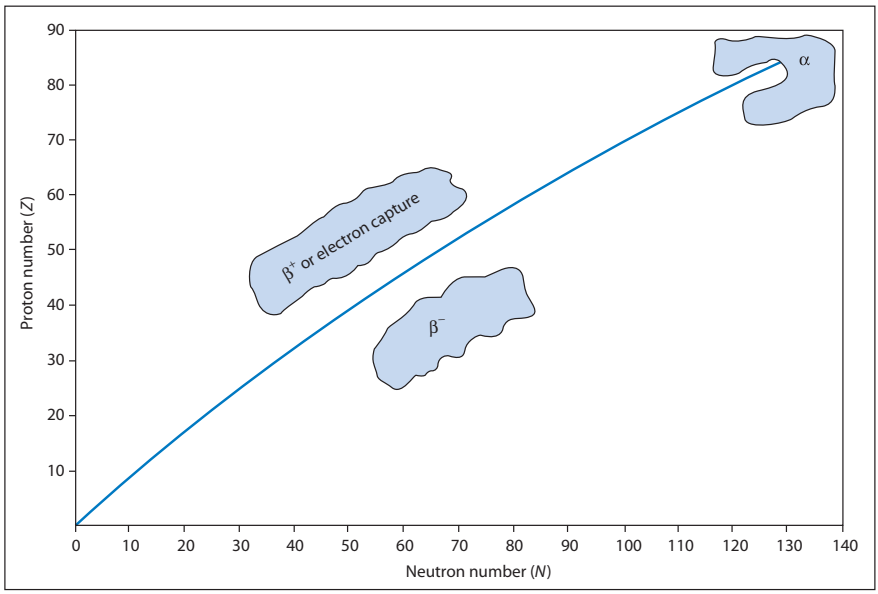

Figure 2.8 The line of stability where the neutron to proton ratio is approximately one.

mass less than 14). These too tend toward instability. Nuclides tend eventually to attain the most stable ratio possible via radioactivity, emission of particles, and/or photons.

Studying a plot of neutron to proton ratio, as it occurs in elements, illustrates, first, that a neutron to proton ratio of approximately one is stable. This line is named the 'line of stability' and has a slope of one (Figure 2.8). Nuclides 'try' to attain the highest possible stability, a position as close as possible to the line of stability. A neutron to proton ratio that is *greater than one* is above the line, indicating excess protons. The nuclides tend to correct themselves by getting rid of some positive charge. This is accomplished via positron emission or electron capture, both of which will be discussed below. A proton is converted to a neutron, and a positron (β^+, a **positively charged electron**) is discharged from the nucleus. Below the line of stability, the neutron to proton ratio is *less than one*, indicating excess neutrons. When this occurs, the nuclides tend to correct themselves by getting rid of some negative charge. This is done via beta (a fast-moving electron from within the nucleus) emission. At the same time, a neutron is converted to a proton and the beta (β^-) particle is ejected from the nucleus. All of these emissions will be discussed in more detail.

Types of radioactive decay

There are two reasons for radioactive decay in an atom. The first is a neutron to proton ratio greater than, or less than, one. The second reason for

radioactive decay is an energy imbalance that creates the need for the atom to rid itself of energy in order to attain greater stability.

As mentioned above, two units are used when discussing the potential for radioactive decay and the magnitude with which it occurs. These are the AMU where one AMU is equal to 1/12th the mass of a ^{12}C nucleus. The second is the electronvolt (more conveniently, the MeV [a million electronvolts, or a mega-electronvolt] and keV [kiloelectronvolt]). Gamma emissions tend to be lower in energy than particulate emissions, so are normally expressed in kiloelectron-volts. The β^- and β^+ emissions have higher energy, so the megaelectronvolt is more commonly used as a unit for their energies. The types of radioactive decay are outlined below. Some are useful in nuclear pharmacy and nuclear medicine, while others are not. All of them need to be understood, however, since they can all impact the performance of the radiopharmaceutical, and since they are important for personal protection from radioactive emissions.

For all emissions, the end products of their interactions with matter are ionization and excitation. Ionization is the creation of positive or negative charges, and this is what we observe with equipment especially made for detecting particular types of radiation and specific energy ranges. Detection is a combination of when radiation interacts with matter and when we observe the effects through the equipment.

Alpha decay

Alpha particles are ionized helium atoms and can be a means of radioactive decay from the nucleus (Figure 2.9). Alpha decay occurs in elements with higher atomic mass, usually those with a heavy nucleus, such as radon or uranium, and those in which the neutron to proton ratio is very high (Figure 2.8).

The emission is particulate, so it carries a set amount of energy away from the nucleus. This causes the emission to be monoenergetic for the particular element in question. The helium nucleus (He^{2+}; 2n + 2p) is a massive 4 AMU particle with a 2+ charge. The nuclear state equation shows that the atomic mass number A decreases to $A-4$, the number of protons Z decreases to $Z-2$, and the number of neutrons N decreases to $N-2$ (Figure 2.10).

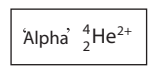

Figure 2.9 The alpha particle.

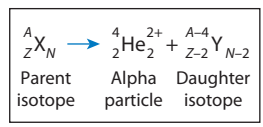

Figure 2.10 The nuclear equation for alpha decay.

Since alpha emission occurs in elements of high atomic number, those in which Z is greater than 82, these nuclides are rarely used in biological systems or nuclear medicine. This is because elements of high Z number are uncommon in biological systems (e.g. the human body).

Alpha particles move at a relatively slow velocity, a small fraction of the speed of light, and, being relatively massive, tend to follow a straight path through most materials. The particles carry a high kinetic energy, in the range 4–8 MeV. They lose energy by interacting with two electrons to neutralize the charge. The result is neutral helium ($He^{2+} + 2e^{-} \rightarrow He^{0}$).

The energy loss from the particle occurs because the particle, which is passing through matter, incurs elastic collisions with atomic electrons. This usually leads to ionization of the target, ultimately culminating in the alpha particle picking up the two electrons.

Because of their very biologically damaging characteristics, alpha-emitting isotopes have little use in nuclear pharmacy and nuclear medicine, other than the potential therapeutic applications. In addition, alpha particles are difficult to detect because of their short range, so they have little utility for imaging.

There are two main mechanisms by which alpha particles interact with matter: excitation and ionization. Excitation, which occurs less frequently than ionization, occurs when an alpha particle's collision with an electron raises the electron to a higher, outer shell. Then, as the electron falls back to its original shell, it emits this excess energy. Only a small portion ($< 5\%$) of the alpha particle energy is imparted, and because this is insufficient for overcoming electronic binding energy, electrons are not removed from the target atom. Therefore, there is little need to worry about personal protection when dealing with this type of interaction with matter.

The second, and more important, mechanism of alpha interaction with matter is the ionization of target atoms. Ionization occurs when the alpha particle is able to strip away an atom's orbital electron, creating a positively charged target ion. Meanwhile, the electron joins the alpha particle, leaving it with a 1+ charge. This phenomenon is called ion-pair formation. The alpha particle may continue making secondary ion-pairs until, ultimately, a chain reaction can occur, initiated by the primary and secondary ionizations that originated from the alpha particle.

The majority of ionizations caused by alpha particles do not involve direct interaction with the initiating alpha particle. Instead, they involve secondary reactions. As 34 eV is sufficient energy for ionization (ion-pair formation) to occur in an atom, a highly energetic alpha particle has more than enough energy to cause many ionizations before its energy is exhausted. As an alpha particle slows down, it has more time for interaction and, therefore, the likelihood of ion-pair formation is enhanced. The lower the alpha particle energy, the slower moving the particle is and the more ion-pairs are produced. For example, if the

Table 2.1 Linear range of 7 MeV alpha particles in various materials

Material	Penetration (μm)
Air	59,000
Water (tissue)	74
Aluminum	34
Mica	29
Copper	14
Lead	2

emission was a 6.8 MeV alpha particle, 2×10^5 ions could be created before its energy was completely dissipated (Wang *et al.* 1975, pp. 41–42).

The **specific ionization** is the number of ion-pairs per unit length in air. For alpha particles, this is dependent on the energy with which the alpha particle is ejected from the nucleus. Being massive, alpha particles do not have excessive ranges in materials. For a 7 MeV alpha particle, penetration in general is only a few centimeters in air, 74 μm in water, and 2 μm in lead (Holloway *et al.* 1938) (Table 2.1).

Beta decay (negatron)

A beta particle is essentially an electron ejected from the nucleus at high velocity. Beta decay occurs when the neutron to proton ratio is greater than one. Inside the nucleus, a neutron is converted to a proton and β^- particle, with an antineutrino carrying away from the nucleus any excess binding energy above the energy of the β^- particle. Any excess energy may be emitted as gamma radiation, which will be discussed below. An antineutrino, a small particle with non-zero mass, has a velocity near the speed of light and has no charge (Figure 2.11).

The effects on A, Z, and N are as follows: Z increases to $Z + 1$, N decreases to $N - 1$, and the antineutrino is emitted. It should be noted that β^- particles

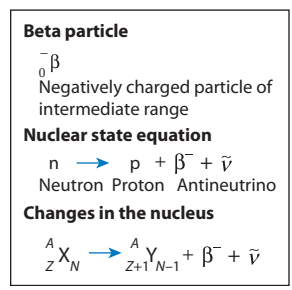

Figure 2.11 The beta particle and the nuclear equation for beta decay.

are energetic electrons in 'appearance,' but β^- particles differ from electrons in that they originate from inside the nucleus. Electrons are in orbit outside the nucleus and have no energy in their normal condition.

A beta particle is very different from an alpha particle. Weighing in at 1/7300th the mass of an alpha particle, a beta particle is considered 'very light.' Both β^- and β^+ are charged particles, but, unlike alpha particles, they have an extremely small mass and velocities that approach the speed of light. They travel in a haphazard path, caused by deflection. Because of their relatively high velocity, they have less time than alpha particles to interact with the target atoms and orbital electrons they pass. However, beta particles have higher penetrating power than alpha particles and a much longer range, a range that is as long as several meters in air. Dissipation of beta particle energy occurs when a β^- encounters a positive charge or a β^+ a negative charge, and ionization and ion-pair formation occur.

Unlike alpha particles, beta particles are not monoenergetic for a particular radionuclide but are emitted at varying energy levels over a continuous range. The antineutrino, for beta decay, and neutrino, for positron decay (below), carry some energy with them as part of their respective beta decay processes. A specific beta energy range is emitted, depending on the isotope of origin (Loevinger, 1957). Therefore, beta particles can be characterized by drawing a graph of the number of particles, or observed intensity, versus particle energy. Of interest, are the following two quantities for the same spectrum: the average energy of emission (E_{avg}) for that particular spectrum and the maximum energy emitted (E_{max}) (Franz *et al.* 1936) (Figure 2.12). The average energy of beta emission can be estimated as one-third the maximum energy of emission: $E_{avg} = {}^1/_3 E_{max}$.

The emitting isotope can be identified by these two values. Values for E_{max} range from 0.019 MeV (19 keV) for ^{3}H up to 4.81 MeV for chlorine-38 (^{38}Cl).

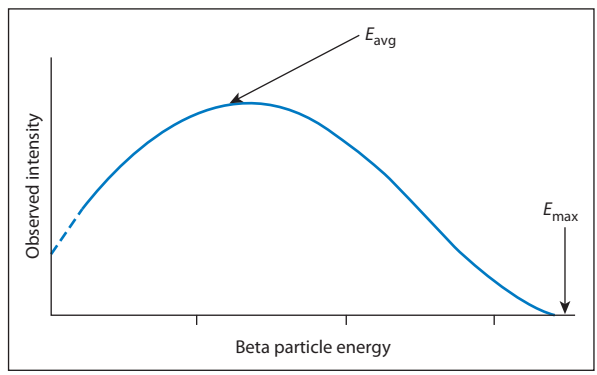

Figure 2.12 A typical beta particle energy distribution curve, showing the average energy of emission (E_{avg}) and the maximum energy emitted (E_{max}). Note that E_{avg} does not always correspond with the highest point on the curve.

For beta particles not at E_{max}, the antineutrino takes on the remaining energy. Consequently the energy emitted from the nucleus has E_{max} (i.e. E_{max} is made up of β^- emission and the antineutrino); beta decay is $n \rightarrow p + \beta^- + \tilde{\nu}$ (energy $= E_{max}$); positron decay is $p \rightarrow n + \beta^+ + \nu$ (energy $= E_{max}$). A beta particle persists after dissipating all of its kinetic energy and usually becomes an atom's orbital electron.

Beta particles can be roughly categorized as 'hard' or 'soft' particles. Hard beta particles normally are those with an E_{avg} above 200–300 keV, while soft betas are under 200 keV. Because maximum ion-pair formation occurs at lower energy levels, the slower, softer beta particles make more ion-pairs than do the harder, faster beta particles. As mentioned above, ionization and ion-pair formation are means by which beta particles interact with matter and dissipate their kinetic energy.

Another mechanism by which β^- particles may interact with matter is through **Bremsstrahlung radiation**. Bremsstrahlung means 'braking radiation.' It occurs as a beta particle passes a positively charged nucleus. The beta particle is attracted and accelerated by the nuclear force field. Excess energy from acceleration is given off in the form of electromagnetic radiation (bremsstrahlung). The result is the emission of a gamma photon (Figure 2.13). This is more likely to occur near elements of high Z numbers such as lead (when approximately 10% of the beta energy is given away), because they have an abundance of protons, and have higher beta energies. These high Z materials attract the β^-, causing bremsstrahlung. For this reason, beta emitters are stored in containers of low Z numbers, such as lucite, in order to reduce exposure of personnel to the resulting electromagnetic radiation. Such exposure would occur if beta emitters were stored in *high* Z number containers such as lead.

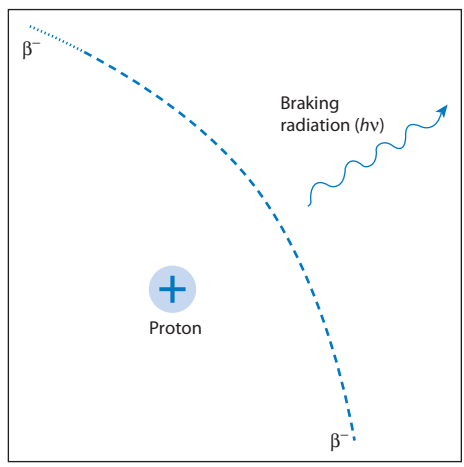

Figure 2.13 Bremsstrahlung or 'braking' radiation. As the β^- passes a proton, it is slowed (but not captured) and releases radiation.

A practical consideration is the need to measure beta particle emission. Alpha particles, having an exceptionally short range, must be measured at approximately 1 mm from the source; whereas beta particles, because they travel farther, can be measured farther from the source.

Beta particles can be used for imaging purposes, but, because of their ionization and excitation characteristics, they are more useful for their therapeutic applications.

Positron decay

Positrons are positively charged beta particles. They are emitted when the neutron to proton ratio is less than one, meaning the atom is proton rich. When a proton is converted to a neutron, a positron (β^+) and a neutrino (opposite of the antineutrino) are ejected. A neutrino is a small particle with almost no mass and no charge. It has a velocity near the speed of light, and carries away the energy difference between the atomic binding energy and the positron energy, if there is any. The nuclear state equation is a proton being converted to β^+ and a neutrino. The changes in the nucleus are a decrease in Z to $Z-1$, an increase in N to $N+1$, and emission of the neutrino (Figure 2.14).

Positrons are identical to beta particles except in charge. A positron has only a transient existence. After losing all of its kinetic energy, it interacts with an electron and is 'annihilated.'

What actually occurs is that both the mass of the positron and the mass of the electron are converted to energy during annihilation. Since each particle has the energy equivalence of 0.511 MeV, 1.022 MeV is the amount of energy that is released upon annihilation. Recall that a beta particle and an electron are basically the same with regard to charge and potential energy. Except for its charge, a positron is like a positively charged electron, in that it has characteristics of both an electron and a beta particle. From this annihilation, 0.511 MeV gamma rays are emitted at a 180° angle to each other (Figure 2.15). The predictability of 180° gamma photon release is the basis for positron emission tomography (PET) detection and the very good imaging properties of positron-emitting isotopes. One important positron decay for imaging purposes is that of ^{11}C: $^{11}C \rightarrow {}^{11}B + \beta^+$. Use of PET will be covered in detail in Chapter 7.

The energy graph for positrons differs slightly from that of beta particles, in that the E_{max} tends to be at a lower particle energy for positrons, and the positron range tends to be shorter (Figure 2.16).

Nuclear state equation

$$p \rightarrow n + \beta^+ + \nu$$

Proton Neutron Positron Neutrino

Changes in the nucleus

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-1}Y_{N+1} + \beta^+ + \nu$$

Figure 2.14 Positron emission: the nuclear state equation and changes in the nucleus.

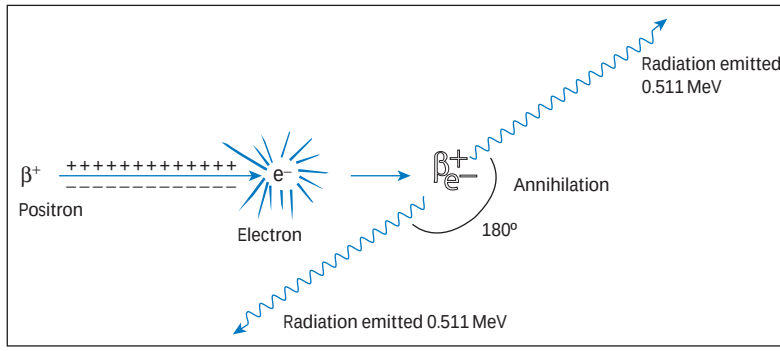

Figure 2.15 Positron annihilation. The mass of the positron and that of the electron are converted to energy during annihilation, which is released as two photons of 0.511 MeV each, at 180° to each other.

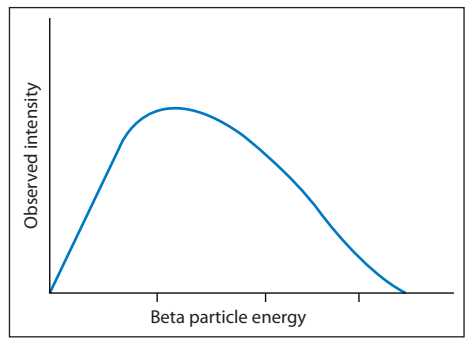

Figure 2.16 Typical energy curve for positron emission.

With positron emission, a stable nucleus is achieved. This usually occurs in elements with low Z numbers, for example $^{13}N \rightarrow {}^{13}C$ (stable).

When a proton is converted to a neutron and a β^+ particle, a mass the equivalent of two electrons is created. To maintain the conservation of energy for β^+ emission, there needs to be at least 1.022 MeV of excess nuclear energy for positron emission, which is the amount of energy required to produce the two 0.511 MeV gamma photons.

Gamma emission

The nucleus can eliminate excess excitation energy by means of photon emission. Photon emission can result from isomeric transition (discussed below), or it can occur randomly to balance the energy lost from the nucleus through a prior decay event. A gamma photon has no charge and occurs as electromagnetic radiation traveling at the speed of light. It has the longest range of any nuclear emission. Gammas have no mass, and the nucleus undergoes no atomic number change or neutron number change upon emission (Figure 2.17). Gamma emission occurs following other types of decay (β^-, β^+, electron capture, or alpha). Normally the parent and daughter are isomers, though they can be isobars, isotopes, or isotones if more than one step is involved.

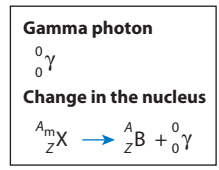

Figure 2.17 The gamma photon.

The emitted photons are monoenergetic (all of the same energy or set of energies), so there is no need for an energy graph.

As with all radiation, gamma radiation is the correction of energy in the radionuclide from a higher energy state to a more stable state. The radiations occur at short wavelengths, 0.1–10 μm (10^{-3} to 10^{-1} Å), and therefore have high energies. The energy range is 1 keV–10 MeV, though most are between 10 keV and 3 MeV (Figure 2.18). For comparison, consider that X-rays generally have energies between 10 eV and 100 keV.

Gamma photons have high penetrative powers, up to several meters. They penetrate matter easily, with little interaction, because, unlike alpha and beta particles, they are not ionized. This results in their range being much greater than that of either alpha or beta particles. In air, a typical alpha particle may have a range of 2–8 cm, a beta particle 0–10 m, and a gamma photon from 1 cm up to 100 m.

Gamma photons interact with matter through direct collisions with nuclei and orbital electrons. Being monoenergetic, many gamma-emitting isotopes are extremely useful as components of imaging radiopharmaceuticals because the photons can be isolated and processed by the imaging equipment used in the nuclear medicine department.

Electron capture and X-ray emission

Electron capture (K-capture, EC), an alternative mechanism to positron emission, allows a nucleus to decrease the number of protons it contains, and achieve *nuclear* stability. Electron capture occurs when the neutron to proton ratio is less than one (excess of protons). During electron capture, an inner orbital electron is captured and drawn into the nucleus. This effectively changes a proton to a neutron, with a neutrino carrying any excess energy from the conversion: electron + proton → neutron + neutrino (ν). Similar to beta decay, the products of electron capture are isobars and therefore are different elements. The product element may also remain unstable, causing it to emit gamma photons or conversion electrons in order to discharge more energy.

Typically, a cascade reaction ensues, usually starting from the K shell. There can be an N capture or L capture, or other orbital electron capture. The end result is that electrons from outer shells move to fill vacated shells closer to the nucleus.

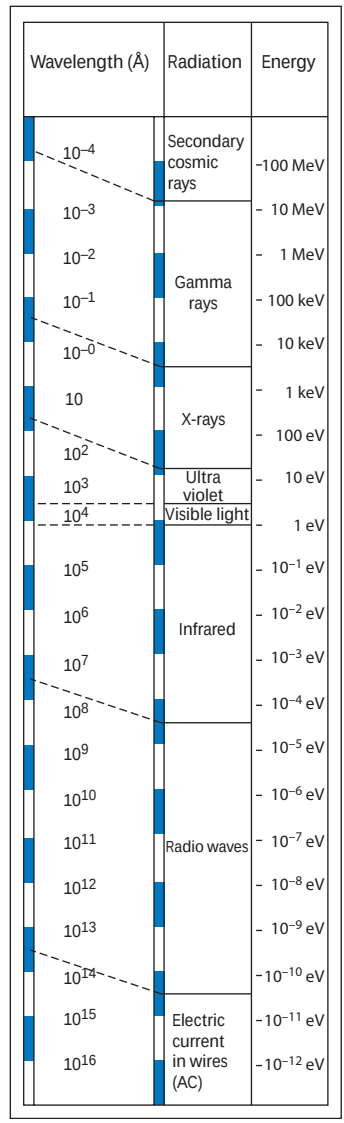

Figure 2.18 The electromagnetic spectrum.

Electrons lose potential energy when they move inward toward lower potential energy orbits, and give off X-rays as they come closer to the nucleus. These emissions are called 'K X-rays,' or 'L X-rays,' depending on the shell of origin. It should again be emphasized that gamma rays are predominantly from inside the nucleus, and X-rays are from outside the nucleus.

For electron capture, the parent and daughter energy differences *usually* are less than 1.022 MeV, which differs from the requirements for positron emission. Another difference between electron capture and positron emission is that electron capture usually occurs in elements of high Z number, whereas

positron emission occurs in elements of low Z number. Because electron shells in these elements are closer to the nucleus, the probability of electron capture being the decay modality increases along with the increasing Z number. As with positron emission, the net result of electron capture is the loss of a proton and gain of a neutron.

Isomeric transition and gamma radiation emission

Recall that isomers differ from one another because the parent nuclide is in an excited state. The *nucleus* of the parent nuclide can remain in an excited (isomeric) energy state. These isomeric nuclei decay to a ground (stable) state. The decay from an excited state to a lower energy state is called isomeric transition. Isomeric transition can accompany β^-, β^+, and electron capture decays. The energy difference between isomeric energy states may appear as gamma radiation. If the isomeric state is long lived enough to be measurable, it is called a **metastable state** and is denoted by an 'm' (e.g. ^{99m}Tc).

Internal conversion: another isomeric transition

When a gamma photon from the nucleus strikes an orbital electron (called a conversion electron), the electron is given energy. The extent of the energy transferred from the gamma photon to the electron depends on the angle at which the electron is struck. If the imparted gamma energy (conversion energy) is higher than binding energy of the electron, the orbital electron is dislodged at a high velocity from its orbit. The phenomenon is called electron conversion. This internal conversion is at a discrete energy, since the causative gamma impact has a discrete energy. As typically occurs during electron capture, the vacated orbital leads to a cascade of electrons filling subsequent orbital vacancies. The conversion *electrons* are also monoenergetic, which leads to the emission of an X-ray as a means of giving up kinetic energy to attain lower potential energy (Figure 2.19). Internal conversion is more

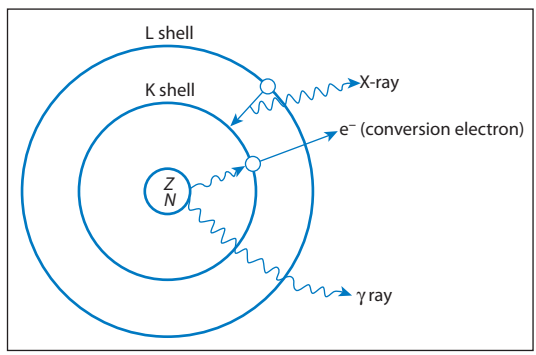

Figure 2.19 Internal conversion. The excess energy of the nucleus is initially given off as a gamma photon. This gamma photon strikes an orbital electron, ejecting it from the atom. The vacancy left by the ejected electron is then filled by electrons from the outer orbitals, which leads to secondary X-ray emission(s).

common with higher atomic number elements and transitions involving lower energy gammas.

Extranuclear events leading to X-rays and the Auger electron

These are emissions resulting from electron capture or internal conversion that cause disruption of the electron cloud. Two types of emissions can occur.

As discussed above, X-rays can be produced by the displacement of orbital electrons and the subsequent replacement of the missing electron(s). These X-rays are quantified using **fluorescence yield**, the energy difference between the orbitals of the shifting electrons. Fluorescence yield is the probability of X-ray emission caused by orbital electron displacement (Figure 2.20). Fluorescence yield is calculated via the probability of the number of X-rays emitted per number of spaces available to be filled. The probability is expressed as the inverse of the fluorescence yield (1/Fl Yld).

The second type of emission is the **Auger electron**. This method for eliminating energy occurs during isomeric transition as an alternative process to X-ray emission. When the originally displaced electron energy is transferred to another outer electron, it knocks the latter out of the atom (Figure 2.20). (This is analogous to internal conversion.) The Auger electron is a monoenergetic electron emission.

Elements with low Z numbers favor Auger electron emission, while those with high Z numbers favor X-ray emission (Figure 2.20). It follows that the probability for X-ray emission increases as Z increases. For X-ray emission to occur, its energy must be at least equal to that expended during the orbital rearrangement process: $E_{\text{X-ray}} = \text{BE}_{\text{original}} - \text{BE}_{\text{final}}$, where BE is the binding energy of the electron.

For Auger electrons to occur, the transition energy must exceed the electron binding energy. Otherwise, the emission will be an X-ray: $E_{\text{Auger}} = E_{\text{X-ray}} - E_{\text{ejected electron}}$, where $E_{\text{X-ray}}$ is the energy of the X-ray that would have been released had there been insufficient energy to expel the second electron.

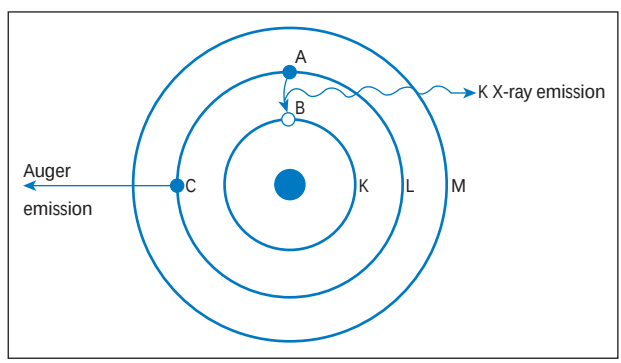

Figure 2.20 X-ray and Auger electron emission are both mechanisms to fill vacated electron orbitals.

Usually, X-rays are emitted as a result of electron capture or internal conversion, and they reflect the energy differences between the orbital electrons. The energy range is from a few electronvolts up to approximately 120 keV. The X-rays from electron capture or internal conversion are of little use in nuclear pharmacy or nuclear medicine but need to be understood for reasons of radiation protection and development of useful radioisotopes.

Photoelectric effect

This occurs when a gamma photon collides with a bound inner electron, which is usually the first K shell electron. This produces an electron with energy equal to that of the impinging gamma photon, and this, in turn, creates an ejected electron. If there is complete energy transfer, then $E_{e^-} = E_\gamma - E_{BE}$. To dislodge the orbital electron, the binding energy must equal the energy of the gamma. (All energy must be transferred for the photoelectric effect.) The loss of the orbital electron induces a cascade, and kinetic energy is lost for conservation of energy. The requirement for energy loss causes X-ray or Auger electron emission. Photoelectric electrons are in the 0–0.5 MeV range. We then detect this resultant ionization. The photoelectric effect usually occurs with elements of high Z number (e.g. there is a better chance of this happening with lead than with aluminum).

Compton effect

This is the decrease in energy (increase in wavelength) of an X-ray or gamma ray photon when it interacts with an outermost shell electron. In contrast with the photoelectric effect, only a *portion* of the gamma energy is given to the electron, leaving a lower energy gamma photon and a displaced electron; for example, there is an 80% to 20% energy distribution for the gamma photon and electron, respectively. There is a high energy spread for the resultant gamma photons and recoil electrons, since there is variability in energy transfer from the initial gamma photon. The maximum energy is imparted to the electron if the electron reflects backwards along the path: '180° backscattering' of the photon (Figure 2.21). The resultant electron and lower energy gamma photon can then cause ionization of other atoms. The higher the energy of the gamma photon, the higher the imparted energy to the electron. The Compton effect commonly occurs with gamma photons of medium energy, in the range 0.5–1.5 MeV. It is also common in atoms of low to medium Z numbers.

Pair production from a gamma strike

This occurs when there is a direct hit by a gamma photon on a nucleus, resulting in the creation of an electron and a β^+ (Figure 2.22). The pair then undergoes annihilation, and some energy is lost to the nucleus during the interaction. This can only occur if there is enough energy available to create the pair (at least the total rest mass energy of the two particles), thus conserving both energy and momentum. For all of this to occur, the interaction must

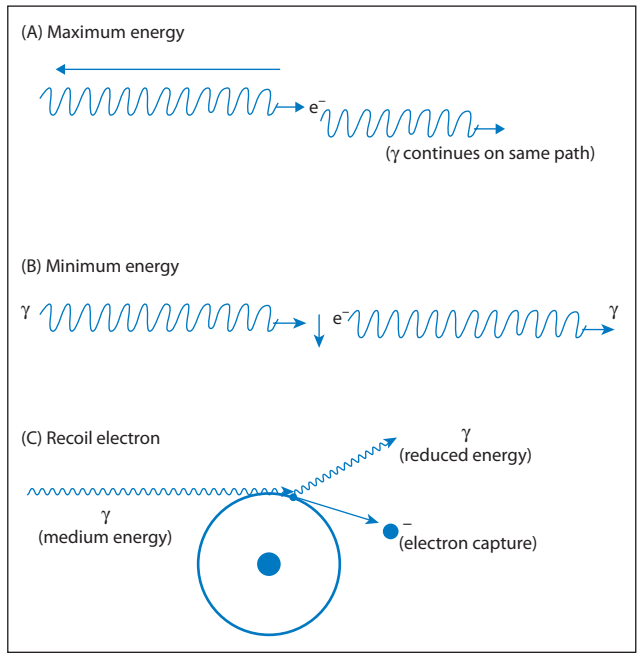

Figure 2.21 The Compton effect. (A) The maximum energy is imparted to the orbital electron by 180° backscattering. (B) The minimum energy is imparted by a 90° strike. (C) Formation of a recoil electron.

start with more energy than 1.022 MeV, the sum of the energy of two annihilation gamma photons. Although the energy is not symmetrically given to the resulting components, 1.022 MeV must be supplied to allow for the two annihilation gamma photons, and enough energy exceeding this must be given to account for the creation of the electron. Pair production occurs in elements of high Z number and with high-energy photons, those in the million electron-volt range. The electron and gamma photons can then cause ionization of other atoms.

The emission that is going to occur from these events depends on the Z number of the absorbing material and the energy of the gamma photon (Figure 2.23).

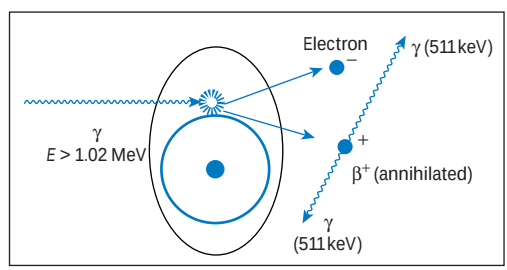

Figure 2.22 Pair production.

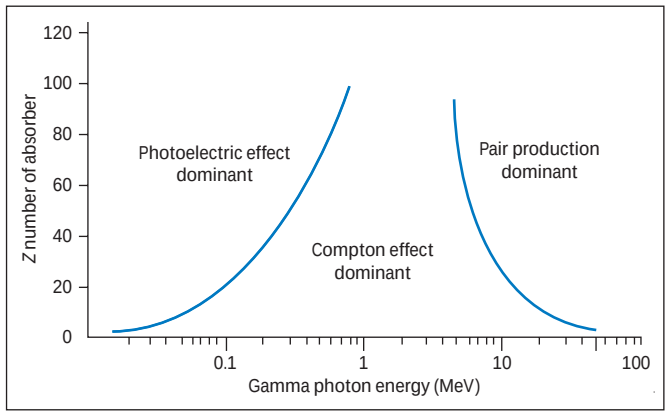

Figure 2.23 Gamma energy in the photoelectric effect, Compton effect, and pair production. The photoelectric effect dominates up to 1 MeV, the Compton effect from 1 to 10 MeV, and pair production above 10 MeV. The interaction type is dependent on the density of the matter and the gamma ray energy.

Nomenclature: decay schemes

Often it is helpful to visualize the decay of an isotope, since it can be complex and information intensive. One way to do this is to look at published **decay schemes** for isotopes. Decay schemes are simple line drawings that allow easier conceptualization of the mechanisms by which isotopes decay, their emission energies, and parent–daughter relationships (Figures 2.24–2.27).

Decay schemes are diagrams designed to help in visualization of the mechanisms by which radioisotopes decay. They use arrows and energy level lines to indicate the type(s) of decay occurring. Since some isotopes undergo more than one type of decay, the percentage 'abundance' of each type of decay and the energies of the decay emissions is also be indicated on the schematic.

Decay schemes help to reveal what is happening with an isotope of interest, including the decay energies that may be available for either imaging or therapy. The types of decay scheme illustrated below are examples of those commonly encountered in nuclear pharmacy and nuclear medicine. They are beta, positron, gamma, and isomeric transition.

The symbol, mass number, and half-life appear on the uppermost horizontal line. If there is more than one decay path, the percentage followed by each is noted in the scheme. The parent and daughter half-lives are indicated in their respective positions on the diagram. An arrow pointing down and to lower right indicates decay by β^- emission. An arrow pointing down and to lower left indicates decay by β^+, α, or electron capture. Gamma emission is represented by a line (usually wavy) moving straight down (Figure 2.26). If the daughter is not stable, multiple decays may occur (polyenergetic decay). The percentage of each type of decay is indicated on the scheme.

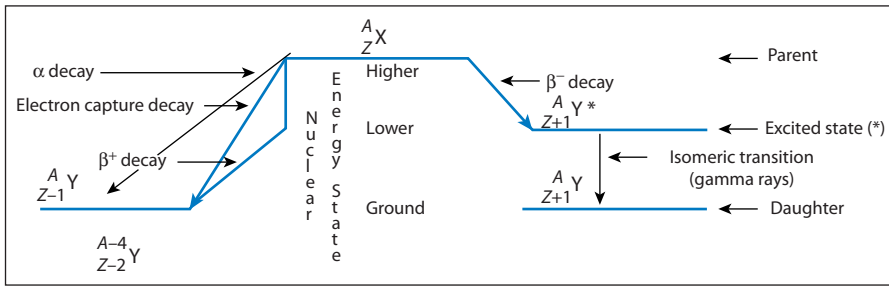

Figure 2.24 Model for general decay schemes.

Beta decay

A β^- decay is represented on a decay scheme as an arrow pointing down and to the right (Figure 2.25). Recall that $E_{avg} = {}^1/_3 E_{max}$. An example is that of iodine-131 (^{131}I), which has a half-life of eight days:

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + \beta^- + \tilde{\nu}$$

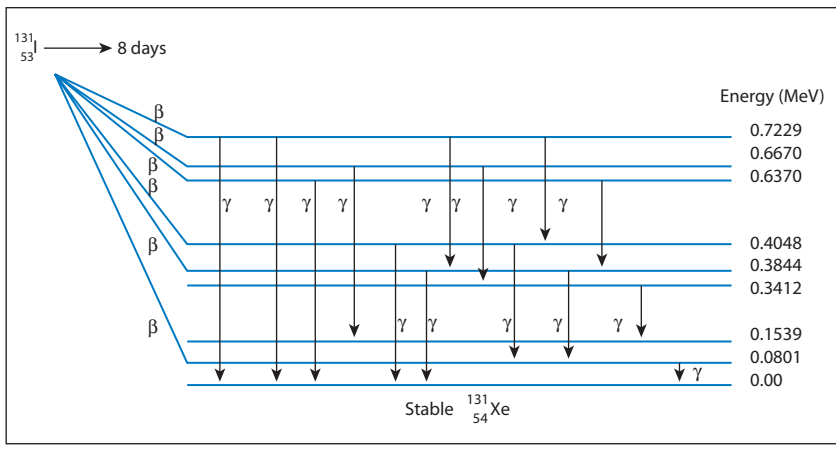

Figure 2.25 Beta decay scheme.

Gamma (isomeric transition) decay

The decay of molybdenum-99 (^{99}Mo) is initially by beta decay but is followed by isomeric transition and gamma emission, resulting in ^{99m}Tc, ^{99}Tc, and finally by another beta decay to ruthenium (^{99}Ru) (Figure 2.26).

$$^{99}_{42}\mathrm{Mo} \rightarrow {}^{99m}_{43}\mathrm{Tc} + \beta^- + \tilde{\nu}$$

$$^{99}\mathrm{Tc} \rightarrow {}^{99}\mathrm{Ru} + \beta^- + \tilde{\nu}$$

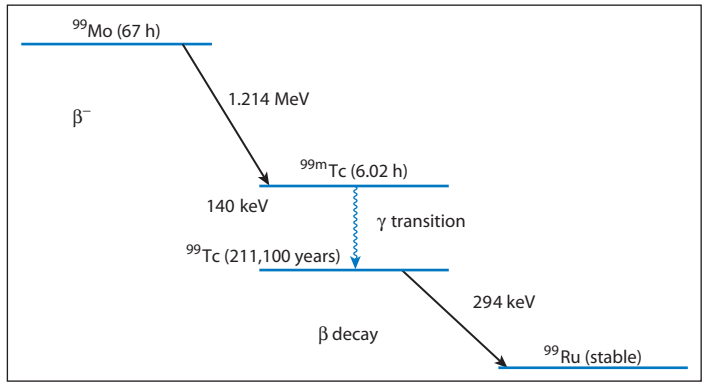

Figure 2.26 Gamma (beta and isomeric transition) decay scheme. Any excess energy left in the nucleus after β^- emission is emitted as gamma radiation.

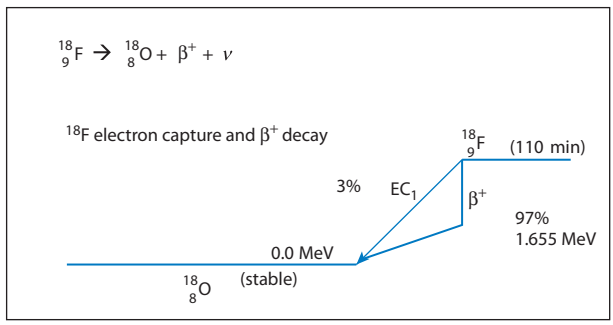

Figure 2.27 Positron decay of ^{18}F: the nuclear state equation and the decay scheme. Any excess energy left in the nucleus after β^+ emission is emitted as gamma radiation.

Positron decay

Figure 2.27 shows positron decay.

Mathematics involved with radioactive decay

According to the fundamental law of decay, the number of atoms that decay is exponential with respect to time, independent of physical properties (such as temperature and pressure), irreversible, and random. Radioactivity is random because it cannot be predicted which atom will decay. Only a probability that it will decay during a given time frame can be quantified. Decay is random for a given nucleus, but, for a large group of the same radionuclide, it follows a first-order decay model, with rate of decay proportional to the remaining radioactive nuclei. Because it is a geometric decay, there is no time on the graph where the number of nuclei is equal to zero.

Decay rate is specific for a particular nuclide. For calculation purposes, N represents the number of undecayed but radioactive nuclei present at time t; N is proportional to the rate of decay, where λ is the decay constant (the fraction disintegrating per unit time), expressed as inverse time for the particular isotope. The symbol λ represents the probability of disintegration for a radioactive atom. Therefore, the disintegration rate is $-dN/dt = \lambda N$. It is negative because radioactive decay is viewed as the loss of nuclei. Rearranging gives $dN/N = -\lambda dt$, and integrating gives $N_t = N_0 e^{-\lambda t}$, where N_0 is the number of atoms at the beginning of the time interval (at $t = 0$) and N_t is the number of atoms remaining after the time interval (t).

For each radionuclide there is a distinct half-life ($t_{1/2}$). The half-life is the time required for a radionuclide to decay to one half its original radioactivity, or simply, from its original 'activity.' After one half-life, N_t is reduced to $1/2N_t$, and the equation becomes $1/2N_0 = N_0 e^{-\lambda t_{1/2}}$. Solving this gives $\ln 1/2 = -\lambda t_{1/2}$. Rearranging leads to $\lambda t_{1/2} = \ln 2$, and further derivation provides $\boldsymbol{t_{1/2} = 0.693/\lambda}$ and $\boldsymbol{\lambda = 0.693/t_{1/2}}$.

Note that $t_{1/2}$ is in time (i.e. seconds), and λ is in reciprocal time (1/time, i.e. 1/s or s^{-1}). Since we use instruments to measure radiation indirectly, we must often consider the efficiency of the detector. Instruments do not measure 100% of all radioactive decays. However, the instrument can be presumed to have a constant error and if we know this constant, we can infer how many disintegrations are occurring per unit of time for a given sample. Decay is often described as disintegrations per minute (dpm), per second (dps), and so on. Our instruments tell us the number of 'counts' they are recording per unit of time. They report counts per minute (cpm), counts per second (cps), and so on. If, in reality, the **disintegration rate** is 1000 dps and the counter has a 70% efficiency, 700 cps will be reported by the instrument.

When describing disintegrations as counts, activity is reported as counts per minute. This can be represented by $A_t = A_0 e^{-\lambda t}$, where A is the activity detected when the same detector set-up is used for detection at both times and the efficiency of the equipment is not changing. 'Activity' means the disintegration rate for any radionuclide. Both equations (that for N_t and that for A_t) are first-order equations and can be graphed in standard Cartesian (Figure 2.28) and semi-logarithmic (Figure 2.29) fashions.

The slope of the semi-logarithmic decay curve is λ. Since $\lambda = 0.693/t_{1/2}$, the half-life can be calculated through cross-multiplication, as $0.693/\lambda$. The number of atoms of an isotope present can be determined using the equation $N = A/\lambda$, where A is activity but presumed to be converted to disintegrations per second, and λ is in units of reciprocal seconds. The mass of an isotope sample can be derived from this equation as well, since the number of atoms present is known.

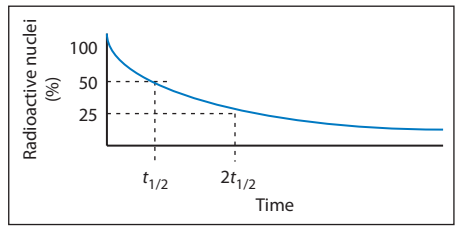

Figure 2.28 First-order decay plotted in Cartesian coordinates.

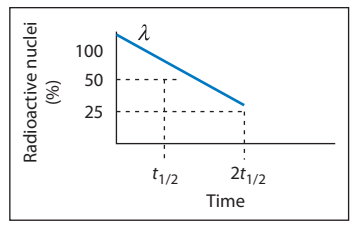

Figure 2.29 First-order decay plotted in semi-logarithmic coordinates. The slope of the line (λ) is the decay constant.

Helpful terms and equations

The number of atoms present at time t can be calculated from the number of atoms present at time 0, the decay constant for an isotope, or the elapsed time, $N_t = N_0 e^{-\lambda t}$ (N here represents the number of atoms). This equation can be arranged to solve for whichever variable is missing.

To find activity rather than number of atoms, the equation $A_t = A_0 e^{-\lambda t}$ may be used or $A_t = A_0/2^n$, where n is the number of half-lives that have occurred.

The **average life** of a group of atoms (τ) is $1/\lambda$ or $1.44t_{1/2}$. This is also called the mean half-life. In one average life time, the activity of a group of a given type of radionuclide is reduced to 37% of its initial value. Since λ is the probability of decay per unit time, $1/\lambda$ is the mean time between decays; $1/\lambda$ has application in calculating exposure and the time required to reach the maximum amount of activity, which will be explained below.

If a radionuclide decays via multiple decay modes, a figure called the effective half-life can be calculated by finding the effective (total) decay constant, λ_e, where λ_e is the multiple of all included λ values divided by the sum of all the λ values:

$$\frac{\lambda_1\lambda_2\lambda_3\ldots}{\lambda_1+\lambda_2+\lambda_3\ldots}$$

Successive decay equations

There are a few unique aspects to calculating the decay rate of parent and daughter isotopes when their half-lives have certain relationships with each other. If they remain in contact with each other, the parent and daughter isotopes can reach a point where both have the same apparent decay rate. If a parent isotope decays to a daughter isotope that also decays, the following is true:

$$dN/dt = \lambda_p N_p - \lambda_d N_d$$

where $\lambda_p N_p$ is the growth rate of the daughter isotope from the decay of the parent and $\lambda_d N_d$ is the decay rate of the daughter. Integration gives

$$(A_d)_t = \lambda_d N_d = \frac{\lambda_d (A_p)_0}{(\lambda_d - \lambda_p)} \left(e^{-\lambda_p t} - e^{-\lambda_d t} \right)$$

If there is initial activity $(A_d)_0$, $(A_d)_0 e^{-\lambda d t}$ is added, and $(A_d)_t$ becomes:

$$(A_d)_t = \lambda_d N_d = \frac{\lambda_d (A_p)_0}{(\lambda_d - \lambda_p)} \left(e^{-\lambda_p t} - e^{-\lambda_d t} \right) + (A_d)_0 e^{-\lambda_d t}$$

Parent–daughter relationships

Transient equilibrium occurs when the half-life of the parent nuclide is slightly longer than the daughter's half-life (Figure 2.30): $(t_{1/2})_p$ can be 10–50 times longer than $(t_{1/2})_d$. If λ_d is greater than λ_p, $(t_{1/2})_d$ is 10–50 times

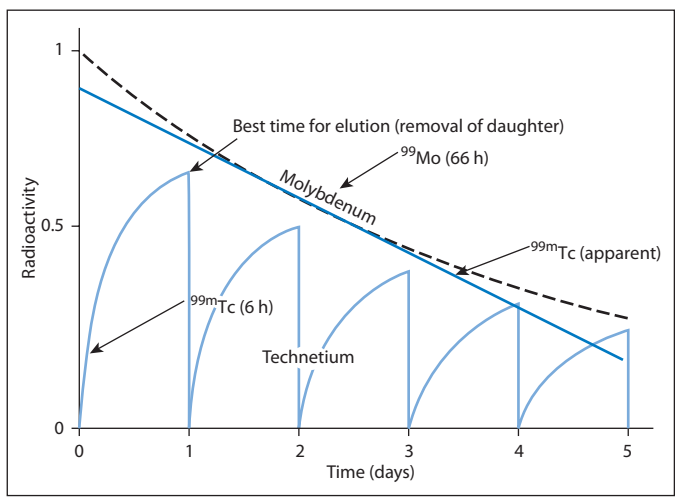

Figure 2.30 Plot of transient equilibrium, demonstrated with the decay of ^{99}Mo.

shorter than $(t_{1/2})_p$. In this case $e^{-\lambda_d t}$ is negligible compared with $e^{-\lambda_p t}$ when t is long enough.

$$(A_d)_t = \frac{\lambda_d (A_p)_0}{(\lambda_d - \lambda_p)} e^{-\lambda_p t} = \frac{\lambda_d (A_p)_t}{(\lambda_d - \lambda_p)}$$

The time to maximum activity is:

$$t_{max} = 1.44 \left[\frac{(t_{1/2})_p (t_{1/2})_d}{(t_{1/2})_p - (t_{1/2})_d} \right] \ln \left[\frac{(t_{1/2})_p}{(t_{1/2})_d} \right]$$

The value 1.44 in this equation comes from $\tau(1/\lambda)$ mentioned above, the average life of a group of atoms.

Figure 2.30 demonstrates this process for the decay of ^{99}Mo ($t_{1/2} = 66$ hours) to 86% ^{99m}Tc ($t_{1/2} = 6.0$ hours) and 14% ^{99}Tc.

If eluted (daughter isotope taken from the source) once a day, the parent regenerates the daughter to the maximum amount possible, up to the amount of parent isotope remaining.

Secular equilibrium occurs when the amount of the daughter isotope remains constant. It remains constant because the rate of decay from parent to daughter is equal to the decay rate of the daughter (Figure 2.31): $(t_{1/2})_p$ exceeds $(t_{1/2})_d$ by 100 times or more. λ_d is much greater than λ_p because the half-life of the parent is much longer than the daughter's half-life. This means that λ_p can be neglected, and $(A_d)_t = (A_p)_t$.

At the beginning, there is no daughter isotope present. Then, the parent decays and builds up the daughter. The loss of the parent isotope eventually comes to an equilibrium with the appearance of the daughter isotope.

The importance of understanding successive decay and the related equations is that many of the radiopharmaceuticals compounded and used in nuclear pharmacy rely on the decay of the parent to daughter nuclide. The daughter nuclide in these cases is the isotope that is useful for imaging or therapy. This set-up is called a **generator** and is self-contained. It is shipped to

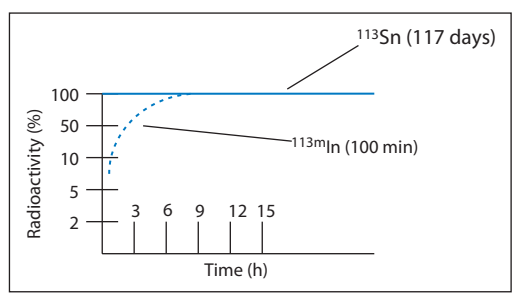

Figure 2.31 Plot of secular equilibrium, demonstrated with the decay of ^{113}Sn.

the pharmacy while the parent nuclide is decaying to the daughter. The daughter is **eluted**, or removed from the generator in its pure (no parent nuclide) form.

It is imperative to know: (1) how much daughter nuclide can be eluted at a given time, (2) the best time to remove the maximum possible amount of daughter nuclide, and (3) the amount of time required for the generator to replenish the daughter isotope after what was available has been removed. To achieve these, it is important to know the parent–daughter relationship and the half-lives of each. Then, a graph and/or computation can be made to determine the best time interval to wait before again eluting the daughter nuclide from the generator.

The terminology used includes the 'growth' of the presence of the daughter isotope and the 'growth rate' from the decay of the parent nuclide.

Effects of radiation on the body: radiation physics and radiobiology

Radiobiology is the study of the effects of radiation on biological systems and, to a great extent, this is also the study of health physics. In familiarizing themselves with these areas of study, nuclear pharmacists become aware of the limits of radiation *exposure*, the radiation *dose*, and the equivalent *dose* that are considered safe for workers and patients. Of ultimate importance is knowing how much radiation and what type of radiation a given part of the body is exposed to and for how much time.

As with other matter, radiation effects on the body include excitation (raising an electron to a higher energy level) and ionization (actual *ejection* of an electron). Radiation causing the latter is called ionizing radiation. Recall that ionization requires roughly 34 eV, which is easily sufficient to break chemical bonds (the carbon–carbon double bond is 4.9 eV). Ionizing radiation can be subcategorized as either electromagnetic or particulate ionizing radiation.

Electromagnetic radiation includes X-rays and gamma rays, all moving at the speed of light but having different wavelengths and, therefore, different energies. When X-rays or gamma rays are absorbed by the body, energy is deposited as the photon is dissipated. Electromagnetic photons are considered to be ionizing if their energy exceeds 124 eV. Particulate ionizing radiation includes alpha, beta, and positron particles plus other particles that are not of concern to nuclear pharmacy.

Radiation can be directly or indirectly ionizing. Charged particles are directly ionizing. Electromagnetic radiation is indirectly ionizing. When photons are absorbed, so is their energy, which can be converted to charged particles via mechanisms such as the Compton and photoelectric effects. Directly and indirectly, ionizing radiation can create free radicals, which,

being very reactive chemically, can cause damage in the cell or in DNA. An example of initial free radical formation can occur with water:

$$H_2O \rightarrow H_2O^+ + e^-$$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH\cdot \text{ (free radical)}$$

The smaller the area of focus of exposure to radiation, the higher the probability of interactions between radiation and the targets, such as DNA, water molecules, and other molecules.

Damage to DNA can cause cell death, mutations, or carcinogenesis. Usually, a single-stranded break is easily repaired by the cell using the opposite strand as a template. If a double-stranded break occurs, especially in slightly offset portions of DNA, the DNA can misrepair (improperly rejoin), leading to cell death or cancerous growth. Therefore, radiation exposure and absorption must be measured. The measurement involves various units.

The units most important to nuclear pharmacy and nuclear medicine are described below. There are actually duplications within these units. Some of the older ones are still in use, and are called 'common units,' while equivalent measurements, such as SI units, are now considered more official. State and federal regulatory agencies set limits for workers, patients, and the general public, but at this point simply the units and their definitions will be introduced (http://www.physics.isu.edu/radinf/terms.htm; http://web.princeton.edu/sites/ehs/radsafeguide/rsg_app_e.htm).

Common terms and units

- *Exposure*. Assessment of exposure has utility in that it is an indicator of how much energy is being emitted into a space, such as a work environment, so it is useful for a quick assessment of electromagnetic radiation workers are, or have been, near.
- *Roentgen (R)*. The roentgen is a measure of exposure, applicable only to gamma and X-rays, and only in air: 1 R is the deposition, in dry air, of enough energy to cause an electric charge of 2.58×10^{-4} coulombs/kg. One roentgen is the amount of radiation required to liberate one unit of positive or negative charge in 1 cm^3 of dry air at standard temperature and pressure. Its main utility is its ease of use in the pharmacy or laboratory for quickly identifying how much exposure one has had to X-rays or gamma radiation.
- *Absorbed dose*. The common unit is the rad (radiation absorbed dose); the SI unit is the gray. It is often useful to assess what has likely been absorbed by tissues in workers or patients from *any* type of radiation in the nuclear pharmacy or nuclear medicine departments. In addition, there is a need to account for the resulting effects that the different types of radiation will

inevitably have on tissues, since particulate and electromagnetic radiations differ in their abilities to inflict damage (see the discussion regarding excitation and ionization above). The equivalent dose can be used to account for these differences.

- *Radiation absorbed dose (rad)*. The radiation absorbed dose (rad) is used to measure absorbed dose and is equal to 10^{-2} J/kg. 1 rad is the absorption of 100 erg/g material. This is the energy given from either particulate or electromagnetic radiation to some material at a specific point.
- *Gray (Gy)*. The gray is the SI unit of absorbed radiation dose from ionizing radiation: 1 Gy is equal to the deposition of one joule of energy per kilogram of a material by any type of radiation. A smaller unit used is 1/100th of a gray, a centigray (cGy). The conversion between gray and rad is 1 Gy = 100 rad.
- *The equivalent dose*. The equivalent dose allows weighting for different types of radiation in order to reflect more accurately differences in their interactions with matter (and tissues). The common unit is the rem (roentgen-equivalent man); the SI unit is the sievert. The weighting is achieved using a *quality factor* (see below), which has been derived from research and is standardized for all radiation workers and patients. It is important to avoid any risk of confusion between the absorbed dose and the equivalent dose by using the corresponding special units, since both are measured in joules per kilogram.
- *Rem (roentgen-equivalent man)*. The rem is a unit quantifying equivalent or effective dose. It relates the dose absorbed in human tissue to the effective biological damage of the radiation. Particulate and electromagnetic radiations have differing effects on tissue, even if the absorbed dose is the same. A smaller unit used is the millirem (mrem), which is 1/1000th of a rem. To calculate the equivalent dose, the absorbed dose (rad) is multiplied by a quality factor (QF) that is unique to the type of radiation. Values for these are shown in Table 2.2.
- *Sievert (Sv)*. The SI unit of equivalent dose is the sievert. A smaller unit used is one-millionth of a sievert, or the microsievert (μSv). To calculate the equivalent dose the absorbed dose (Gy) is multiplied by a quality factor (QF) that is unique to the type of radiation (Table 2.2). The conversion between Sieverts and Rems is 1 Sv = 100 Rem.

Table 2.2 Quality factor assignments for radiation

Types of radiation	Quality factor
X- or gamma-rays	1
Beta particles	1
Alpha particles	20

- *Quality factor (QF)*. The quality factor values Table 2.2 are from the International Commission on Radiological Protection (ICRP) publication 26 in 1978 and revised publication 60 in 1990. These values are based on the type of radiation and the tissue mass in which the energy is distributed (Lawson, 1999), and allow authorities and employers to monitor the potential amount of radiation damage occurring in a person's body. Armed with these numbers, they can intervene if exposure, dose, or equivalent dose exceeds periodic limits. For the nuclear pharmacist, monitoring the pharmacy and personal exposure enables completion of procedures with nominal risk. It is helpful to understand the types of emission occurring in materials being handled so that adequate protection can be used.

Penetration potential

As described above, various emissions have different characteristics, depending on their energies, and whether they are particulate or electromagnetic in nature (Figures 2.32 and 2.33).

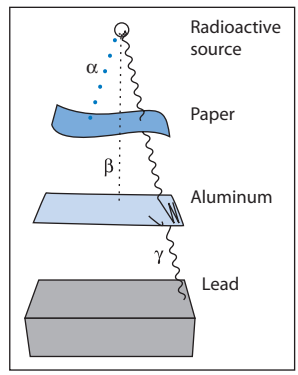

Figure 2.32 Penetration potential in materials for different radiation types.

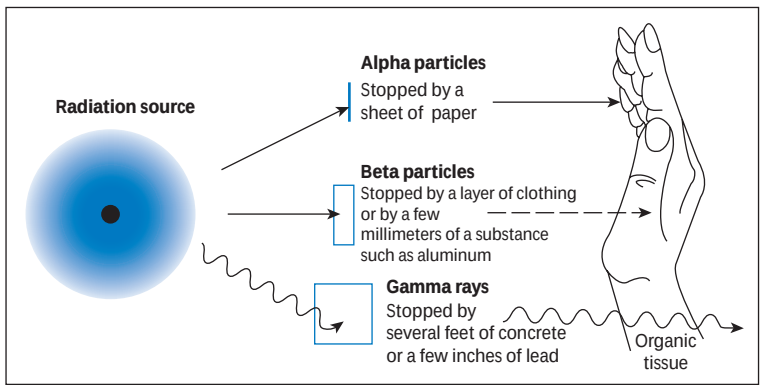

Figure 2.33 Penetration potential in tissue for different radiation types.

Alpha particles

Alpha particles have the shortest range of all the emissions, so only a small distance is required to avoid exposure. Alpha particles can be stopped with paper. They cause effective cell death when in close contact and, therefore, are sometimes used in cancer treatment. If ingested, alpha particles can cause extensive damage in a concentrated area, and, because of their typically long half-lives, provide prolonged exposure.

Skin is thick enough to protect from alpha radiation. One simply needs to wash the hands and avoid breathing it. So, exposure is not normally an issue with alpha emitters, especially since the alpha emitters are rarely used in a nuclear pharmacy. However, being difficult to monitor, exposure can be very insidious.

Beta particles

Ionization and excitation of atoms occur when beta particles interact with matter, similar to the manner in which alpha particles interact with matter. One way beta particle energy is lost is via bremsstrahlung radiation (see above). Beta particles can be stopped by plastic, aluminum, or other materials of low Z number. Therefore, lucite, plastic, glass, or aluminum are used for shielding and protection.

Ingestion of beta-emitting isotopes can have severe consequences, especially radioisotopes of carbon, hydrogen, sulfur, and phosphorus, since these can be incorporated into biochemical materials in the body. They can be deposited in tissues or DNA and cause extensive damage. In addition, many of these isotopes have long half-lives, so they can stay in the body for long periods of time, leading to genetic problems and molecular destruction for many years. Fortunately, beta emission is easy to monitor, so workers can be aware of shielding needs and deficiencies.

Gamma photons

Gamma photon energies usually are larger than chemical bond energies, and can therefore cause chemical reactions or destroy structures in biological (and non-biological) systems. Recall that gamma photons can cause ionization and excitation, though not as effectively as alpha and beta particles.

Shielding requirements for gamma-emitting isotopes depend on the energy of the gamma rays. Low-energy gamma rays require only plastic containers, while high-energy gamma rays require the use of lead or materials of high Z number.

Gamma photons penetrate skin and tissue easily. The photoelectric effect occurs mostly in tissue. There is no ‘safe’ level of exposure to gamma

radiation. However, of the typical emissions encountered in nuclear pharmacy, gamma radiation is the least worrisome regarding tissue damage.

Summary

Atoms consist of three main components: neutrons, protons, and electrons. Atoms are defined by numbers representing the numbers of neutrons, protons, and the sum of the numbers of neutrons and protons. These numbers can be represented schematically by the three letters *N*, *Z*, and *A*, respectively.

Two atoms that differ only in their number of neutrons are called isotopes, while those differing in the number of protons are either isobars or isotones. By virtue of possessing differing numbers of protons, isotones and isobars are actually different elements.

Energy and mass are interchangeable, and the units most pertinent to expressing these are the AMU, erg, and electronvolt.

Atoms may be either stable nuclides or unstable *radionuclides*. If an atom is radioactive, meaning it emits either particulate or electromagnetic radiation, its degree of radioactivity can be expressed in either curies or becquerels.

An element is radioactive because of an energy instability within the nucleus. By emitting various forms of radioactivity, the nucleus is eventually able to attain energy stability. The mechanisms by which atoms rid themselves of energy include beta, positron, and gamma radiations. These emissions interact with matter in either a destructive or medically useful manner. Beta particles can be used therapeutically. Positron and gamma emissions can be used diagnostically.

It is wise for the practitioner to be aware of direct and ancillary radiations that can interact with tissues, sometimes from unsuspected origins.

Decay schemes are often used in order to gain understanding of how radionuclides decay, and by which radioactive emission type.

Radioactive decay follows a first-order mathematical process. By understanding a radioisotope's half-life and decay mechanisms, its use can be optimized. This is true for the preparation and use of radiopharmaceuticals and understanding source materials such as radionuclide generators.

Having an awareness of the effects of radioactivity on the body allows the nuclear pharmacist to safely handle, monitor, and prepare doses of radiopharmaceuticals for patients. Monitoring radiation in the work environment and evaluating radiation exposure to personnel and patients is quantified by using the units of roentgens, rads, grays, rems, and sieverts. Some of these units express the exposure of air to radioactivity, while others express the amount of radiation absorbed by tissues. By using knowledge of the type of radiation encountered, the nuclear pharmacist is better able to assess risks

and benefits of radiation exposure to personnel and patients. This knowledge is based on a sound understanding of radioactivity and radioactive decay.

Self-assessment questions

1 What are the three major components of atoms?
2 What are nucleons?
3 What are the differences among isotopes, isobars, isomers, isotones, and ions?
4 What are the four fundamental forces?
5 Rank the four forces, from most important to least important, in regard to their effects on the nucleus.
6 The mass of ^{32}P is 31.9739 (http://wwwndc.jaea.go.jp/CN04/). (a) Calculate the mass defect in MeV. (b) Calculate the average binding energy for each nucleon.
7 How does the neutron to proton ratio for radionuclides predict whether they will decay by beta, positron emission, or electron capture?
8 Write the nuclear state equations for alpha, beta, and positron decay.
9 Which of the decays mentioned in question 8 has the most energy?
10 Which of the decays mentioned in question 8 has/have use in nuclear pharmacy and nuclear medicine?
11 What are the main mechanisms of interaction with matter for each of the decays mentioned in question 8?
12 Which emission can have bremsstrahlung associated with it?
13 What type of decay is indicated by (a) an arrow pointing down and to the right; (b) down and to the left; (c) straight down?
14 The half-life of ^{32}P is 14.262 days. Calculate its decay constant.
15 Calculate the half-life, in seconds, of an isotope for which $\lambda = 0.0825/h$.
16 A ^{99m}Tc-sodium pertechnitate injection has a labeled activity of 550 μCi. Express this activity in terms of MBq.
17 A ^{201}Tl-thallous chloride (^{201}TlCl) injection has a labeled activity of 132 MBq. Express this activity in terms of mCi.
18 Express the radioactivity in MBq for a substance with 5.15×10^7 dps.
19 How many dps are represented by a material whose activity is 13.25 mCi?
20 At 10:00 am ^{99m}Tc radioactivity was measured as 19 mCi (703 MBq) on a certain day. What was the activity at (a) 8:00 am and (b) 5:00 pm on the same day (half-life for ^{99m}Tc is 6.02 h)?
21 The original quantity of an isotope is measured as 750 μCi/mL (27.8 MBq/mL). If the quantity remaining after 16 days is

187.5 μCi/mL (6.9 MBq/mL), calculate (a) the decay constant and (b) the half-life.

22 Calculate (a) the total number of atoms and (b) the total mass of ^{99m}Tc present in 8 mCi (296 MBq) ^{99m}Tc (half-life 6.02 h).

23 Define the terms roentgen, rad, rem, gray, and sievert.

24 What is the most damaging type of radiation?

25 What radiation has the longest range?

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