chapter 3

Modes of Radioactive Decay

Radioactive decay is a process in which an unstable nucleus transforms into a more stable one by emitting particles, photons, or both, releasing energy in the process. Atomic electrons may become involved in some types of radioactive decay, but it is basically a *nuclear* process caused by *nuclear* instability. In this chapter we discuss the general characteristics of various modes of radioactive decay and their general importance in nuclear medicine.

A. GENERAL CONCEPTS

It is common terminology to call an unstable radioactive nucleus the *parent* and the more stable product nucleus the *daughter*. In many cases, the daughter also is radioactive and undergoes further radioactive decay. Radioactive decay is *spontaneous* in that the exact moment at which a given nucleus will decay cannot be predicted, nor is it affected to any significant extent by events occurring outside the nucleus.

Radioactive decay results in the conversion of mass into energy. If all the products of a particular decay event were gathered together and weighed, they would be found to weigh less than the original radioactive atom. Usually, the energy arises from the conversion of nuclear mass, but in some decay modes, electron mass is converted into energy as well. The total mass-energy conversion amount is called the *transition energy*, sometimes designated Q.* Most of this energy is imparted as kinetic energy to emitted particles or converted to photons, with a small (usually insignificant) portion given as kinetic energy to the recoiling nucleus. Thus radioactive decay results not only in the transformation of one nuclear species into another but also in the transformation of mass into energy.

Each radioactive nuclide has a set of characteristic properties. These properties include the mode of radioactive decay and type of emissions, the transition energy, and the average lifetime of a nucleus of the radionuclide before it undergoes radioactive decay. Because these basic properties are characteristic of the nuclide, it is common to refer to a radioactive species, such as ^{131}I, as a *radionuclide*. The term *radioisotope* also is used but, strictly speaking, should be used only when specifically identifying a member of an isotopic family as radioactive; for example, ^{131}I is a radioisotope of iodine.

B. CHEMISTRY AND RADIOACTIVITY

Radioactive decay is a process involving primarily the nucleus, whereas chemical reactions involve primarily the outermost orbital electrons of the atom. Thus the fact that an atom has a radioactive nucleus does not affect its chemical behavior and, conversely, the chemical state of an atom does not affect its radioactive characteristics. For example, an atom of the radionuclide ^{131}I exhibits the same chemical behavior as an atom of ^{127}I, the naturally occurring stable nuclide, and ^{131}I has the same radioactive characteristics whether it exists as iodide ion (I^-) or incorporated into a

*Some texts and applications consider only nuclear mass, rather than the mass of the entire atom (i.e., atomic mass), in the definition of transition energy. As will be seen, the use of atomic mass is more appropriate for the analysis of radioactive decay because both nuclear and nonnuclear mass are converted into energy in some decay modes. As well, energy originating from either source can contribute to usable radiation or to radiation dose to the patient. For a detailed discussion of the two methods for defining transition energy, see Evans RD: *The Atomic Nucleus*. New York, 1972, McGraw-Hill, pp 117-133.

large protein molecule as a radioactive label. Independence of radioactive and chemical properties is of great significance in tracer studies with radioactivity—a radioactive *tracer* behaves in chemical and physiologic processes exactly the same as its stable, naturally occurring counterpart, and, further, the radioactive properties of the tracer do not change as it enters into chemical or physiologic processes.

There are two minor exceptions to these generalizations. The first is that chemical behavior can be affected by differences in atomic *mass*. Because there are always mass differences between the radioactive and the stable members of an isotopic family (e.g., ^{131}I is heavier than ^{127}I), there may also be chemical differences. This is called the *isotope effect*. Note that this is a *mass* effect and has nothing to do with the fact that one of the isotopes is radioactive. The chemical differences are small unless the relative mass differences are large, for example, ^{3}H versus ^{1}H. Although the isotope effect is important in some experiments, such as measurements of chemical bond strengths, it is, fortunately, of no practical consequence in nuclear medicine.

A second exception is that the average lifetimes of radionuclides that decay by processes involving orbital electrons (e.g., internal conversion, Section E, and electron capture, Section F) can be changed very slightly by altering the chemical (orbital electron) state of the atom. The differences are so small that they cannot be detected except in elaborate nuclear physics experiments and again are of no practical consequence in nuclear medicine.

C. DECAY BY β^- EMISSION

Radioactive decay by β^- emission is a process in which, essentially, a neutron in the nucleus is transformed into a proton and an electron. Schematically, the process is

$$n \rightarrow p^+ + e^- + \nu + \text{energy} \qquad (3\text{-}1)$$

The electron (e^-) and the neutrino (ν) are ejected from the nucleus and carry away the energy released in the process as kinetic energy. The electron is called a β^- *particle*. The neutrino is a "particle" having no mass or electrical charge.* It undergoes virtually no interactions with matter and therefore is essentially undetectable. Its only practical consequence is that it carries away some of the energy released in the decay process.

Decay by β^- emission may be represented in standard nuclear notation as

$$^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y \qquad (3\text{-}2)$$

The parent radionuclide (X) and daughter product (Y) represent different chemical elements because atomic number increases by one. Thus β^- decay results in a *transmutation* of elements. Mass number A does not change because the total number of nucleons in the nucleus does not change. This is therefore an *isobaric* decay mode, that is, the parent and daughter are isobars (see Chapter 2, Section D.3).

Radioactive decay processes often are represented by a *decay scheme diagram*. Figure 3-1 shows such a diagram for ^{14}C, a radionuclide that decays solely by β^- emission. The line representing ^{14}C (the parent) is drawn above and to the left of the line representing ^{14}N (the daughter). Decay is "to the right" because atomic number *increases* by one (reading Z values from left to right). The vertical distance between the lines is proportional to the total amount of energy released, that is, the transition energy for the decay process (Q = 0.156 MeV for ^{14}C).

*Actually, in β^- emission an antineutrino, $\bar{\nu}$, is emitted, whereas in β^+ emission and EC, a neutrino, ν, is emitted. For simplicity, no distinction is made in this text. Also, evidence from high-energy physics experiments suggests that neutrinos may indeed have a very small mass, but an exact value has not yet been assigned.

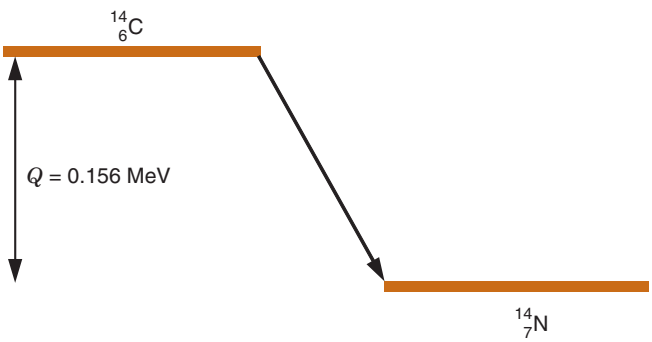


FIGURE 3-1 Decay scheme diagram for ^{14}C, a β^- emitter. Q is the transition energy.

The energy released in β^- decay is shared between the β^- particle and the neutrino. This sharing of energy is more or less random from one decay to the next. Figure 3-2 shows the distribution, or *spectrum*, of β^--particle energies resulting from the decay of ^{14}C. The maximum possible β^--particle energy (i.e., the transition energy for the decay process) is denoted by E_β^{max} (0.156 MeV for ^{14}C). From the graph it is apparent that the β^- particle usually receives something less than half of the available energy. Only rarely does the β^- particle carry away all the energy ($E_\beta = E_\beta^{max}$).

The *average energy* of the β^- particle is denoted by $\bar{E}_\beta$. This varies from one radionuclide to the next but has a characteristic value for any given radionuclide. Typically, $\bar{E}_\beta \approx (1/3)E_\beta^{max}$. For ^{14}C, $\bar{E}_\beta = 0.0497$ MeV $(0.32\,E_\beta^{max})$.

Beta particles present special detection and measurement problems for nuclear medicine applications. These arise from the fact that they can penetrate only relatively small thicknesses of solid materials (see Chapter 6, Section B.2). For example, the thickness is at most only a few millimeters in soft tissues. Therefore it is difficult to detect β^- particles originating from inside the body with a detector that is located outside the body. For this reason, radionuclides emitting only β^- particles rarely are used when measurement in vivo is required. Special types of detector systems also are needed to detect β^- particles because they will not penetrate even relatively thin layers of metal or other outside protective materials that are required on some types of detectors. The implications of this are discussed in Chapter 7.

The properties of various radionuclides of medical interest are presented in Appendix C. Radionuclides decaying solely by β^- emission listed there include ^{3}H, ^{14}C, and ^{32}P.

D. DECAY BY (β^-, γ) EMISSION

In some cases, decay by β^- emission results in a daughter nucleus that is in an excited or metastable state rather than in the ground state. If an excited state is formed, the daughter nucleus promptly decays to a more stable nuclear arrangement by the emission of a γ ray (see Chapter 2, Section D.5). This sequential decay process is called (β^-, γ) *decay*. In standard nuclear notation, it may be represented as

$$ {}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y^{*} \xrightarrow{\gamma} {}^{A}_{Z+1}Y \qquad (3\text{-}3) $$

Note that γ emission does not result in a transmutation of elements.

An example of (β^-, γ) decay is the radionuclide ^{133}Xe, which decays by β^- emission to one of three different excited states of ^{133}Cs.

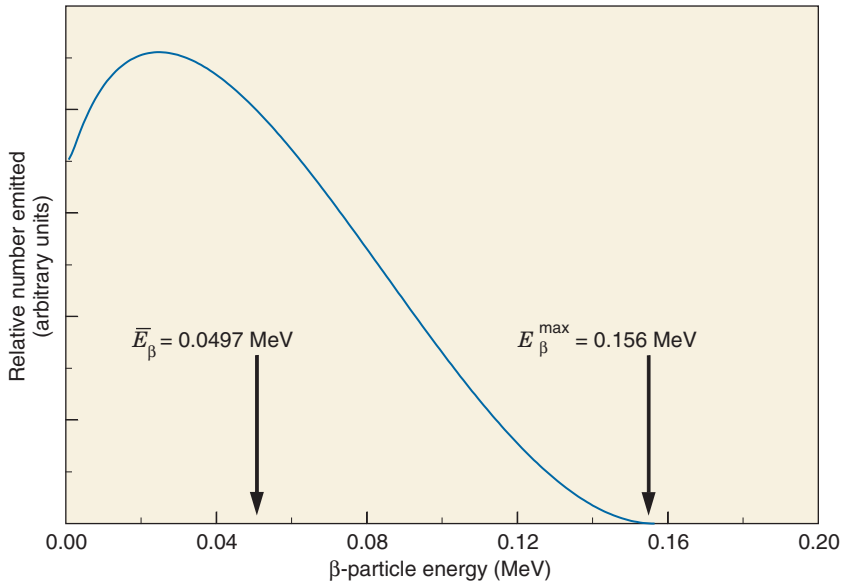


FIGURE 3-2 Energy spectrum (number emitted vs. energy) for β particles emitted by ^{14}C. Maximum β^--particle energy is Q, the transition energy (see Fig. 3-1). Average energy $\bar{E}_\beta$ is 0.0497 MeV, approximately $(\frac{1}{3})\,E_\beta^{max}$. (*Data courtesy Dr. Jongwha Chang, Korea Atomic Energy Research Institute.*)

Figure 3-3 is a decay scheme for this radionuclide. The daughter nucleus decays to the ground state or to another, less energetic excited state by emitting a γ ray. If it is to another excited state, additional γ rays may be emitted before the ground state is finally reached. Thus in (β^-, γ) decay more than one γ ray may be emitted before the daughter nucleus reaches the ground state (e.g., β_2 followed by γ_1 and γ_2 in ^{133}Xe decay).

The number of nuclei decaying through the different excited states is determined by probability values that are characteristic of the particular radionuclide. For example, in ^{133}Xe decay (Fig. 3-3), 99.3% of the decay events are by β_3 decay to the 0.081-MeV excited state, followed by emission of the 0.081-MeV γ ray or conversion electrons (Section E). Only a very small number of the other β particles and γ rays of other energies are emitted. The data presented in Appendix C include the relative number of emissions of different energies for each radionuclide listed.

In contrast to β^- particles, which are emitted with a continuous distribution of energies (up to E_β^{max}), γ rays are emitted with a precise and discrete series of energy values. The spectrum of emitted radiation energies is therefore a series of discrete lines at energies that are characteristic of the radionuclide rather than a continuous distribution of energies (Fig. 3-4). In (β^-, γ) decay, the transition energy between the parent radionuclide and the ground state of the daughter has a fixed characteristic value. The distribution of this energy among the β^- particle, the neutrino, and the γ rays may vary from one nuclear decay to the next, but the sum of their energies in any decay event is always equal to the transition energy.

Because γ rays are much more penetrating than β^- particles, they do not present some of the measurement problems associated with β^- particles that were mentioned earlier, and they are suitable for a wider variety of applications in nuclear medicine. Some radionuclides of medical interest listed in Appendix C that undergo (β^-, γ) decay include ^{131}I, ^{133}Xe, and ^{137}Cs.

E. ISOMERIC TRANSITION AND INTERNAL CONVERSION

The daughter nucleus of a radioactive parent may be formed in a "long-lived" metastable or isomeric state, as opposed to an excited state. The decay of the metastable or isomeric state by the emission of a γ ray is called an *isomeric transition* (see Chapter 2, Section D.4). Except for their average lifetimes, there are no differences in decay by γ emission of metastable or excited states.

An alternative to γ-ray emission is *internal conversion*. This can occur for any excited state, but is especially common for metastable states. In this process, the nucleus decays by

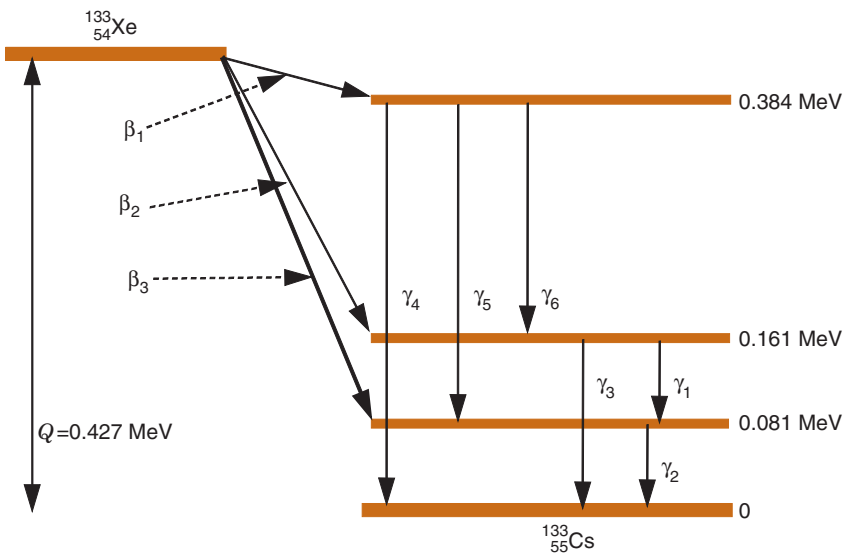


FIGURE 3-3 Decay scheme diagram for ^{133}Xe, a (β^-, γ) emitter. More than one γ ray may be emitted per disintegrating nucleus. The *heavy line* (for β_3) indicates most-probable decay mode.

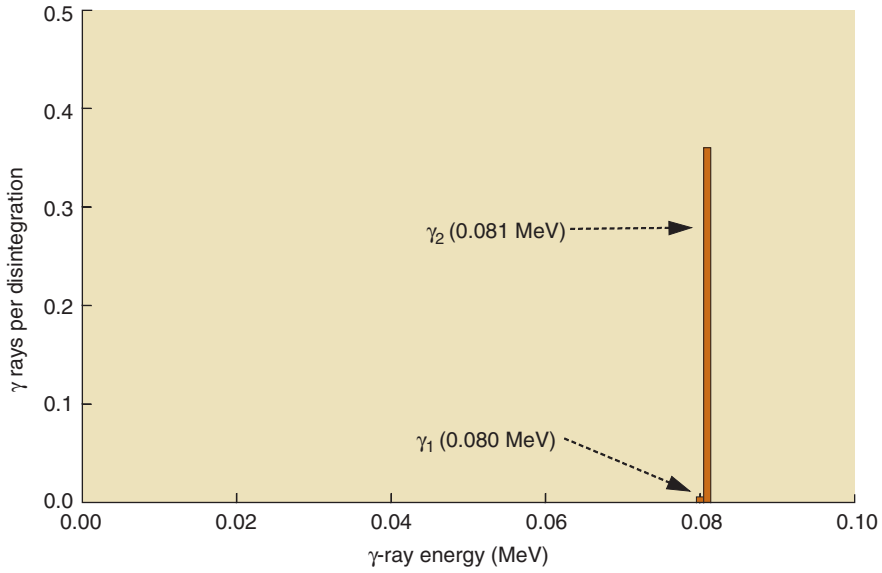


FIGURE 3-4 Emission spectrum for 0.080- and 0.081-MeV γ rays emitted in the decay of ^{133}Xe (γ_1 and γ_2 in Fig. 3-3; higher-energy emissions omitted). Compare with Figure 3-2 for β^- particles.

transferring energy to an orbital electron, which is ejected instead of the γ ray. It is as if the γ ray were "internally absorbed" by collision with an orbital electron (Fig. 3-5). The ejected electron is called a *conversion electron*. These electrons usually originate from one of the inner shells (K or L), provided that the γ-ray energy is sufficient to overcome the binding energy of that shell. The energy excess above the binding energy is imparted to the conversion electron as kinetic energy. The orbital vacancy created by internal conversion subsequently is filled by an outer-shell electron, accompanied by emission of characteristic x rays or Auger electrons (see Chapter 2, Section C.3).

Whether a γ ray or a conversion electron is emitted is determined by probabilities that have characteristic values for different radionuclides. These probabilities are expressed in terms of the ratio of conversion electrons emitted to γ rays emitted (e/γ) and denoted by α (or α_K = e/γ for K-shell conversion electrons, and so on) in detailed charts and tables of nuclear properties.

Internal conversion, like β^- decay, results in the emission of electrons. The important differences are that (1) in β^- decay the electron originates from the nucleus, whereas in internal conversion it originates from an electron orbit; and (2) β^- particles are emitted with a continuous spectrum of energies, whereas conversion electrons have a discrete series of energies determined by the differences between the γ-ray energy and orbital electron-binding energies.

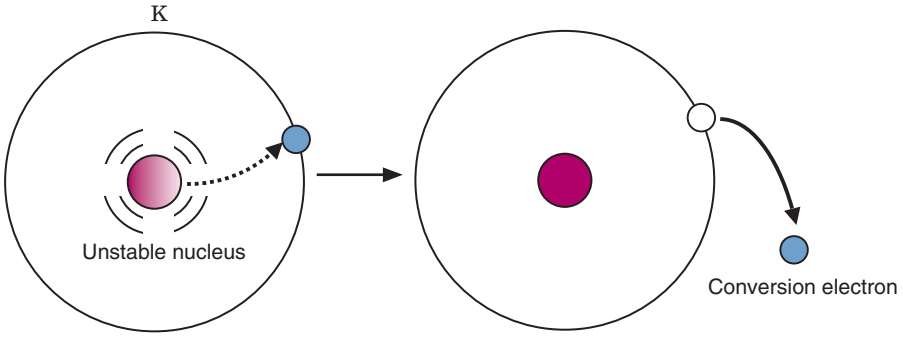


FIGURE 3-5 Schematic representation of internal conversion involving a K-shell electron. An unstable nucleus transfers its energy to the electron rather than emitting a γ ray. Kinetic energy of conversion electron is γ ray energy minus electron-binding energy ($E_\gamma - K_B$).

Metastable radionuclides are of great importance in nuclear medicine. Because of their relatively long lifetimes, it sometimes is possible to separate them from their radioactive parent and thus obtain a relatively "pure" source of γ rays. The separation of the metastable daughter from its radioactive parent is accomplished by chemical means in a radionuclide "generator" (see Chapter 5, Section C). Metastable nuclides always emit a certain number of conversion electrons, and thus they are not really "pure" γ-ray emitters. Because conversion electrons are almost totally absorbed within the tissue where they are emitted (Chapter 6, Section B.2), they can cause substantial radiation dose to the patient, particularly when the conversion ratio, e/γ, is large. However, the ratio of photons to electrons emitted by metastable nuclides usually is greater than for (β^-,γ) emitters, and this is a definite advantage for studies requiring detection of γ rays from internally administered radioactivity.

A metastable nuclide of medical interest listed in Appendix C is ^{99m}Tc. Technetium-99m is currently by far the most popular radionuclide for nuclear medicine imaging studies.

F. ELECTRON CAPTURE AND (EC, γ) DECAY

Electron capture (EC) decay looks like, and in fact is sometimes called, "inverse β^- decay." An orbital electron is "captured" by the nucleus and combines with a proton to form a neutron:

$$p^+ + e^- \rightarrow n + \nu + \text{energy} \qquad (3\text{-}4)$$

The neutrino is emitted from the nucleus and carries away some of the transition energy. The remaining energy appears in the form of characteristic x rays and Auger electrons, which are emitted by the daughter product when the resulting orbital electron vacancy is filled. Usually, the electron is captured from orbits that are closest to the nucleus, that is, the K and L shells. The notation EC(K) is used to indicate capture of a K-shell electron, EC(L) an L-shell electron, and so forth.

EC decay may be represented as:

$$^{A}_{Z}X \xrightarrow{EC} {}^{A}_{Z-1}Y \qquad (3\text{-}5)$$

Note that like β^- decay it is an isobaric decay mode leading to a transmutation of elements.

The characteristic x rays emitted by the daughter product after EC may be suitable for external measurement if they are sufficiently energetic to penetrate a few centimeters of body tissues. There is no precise energy cutoff point, but 25 keV is probably a reasonable value, at least for shallow organs such as the thyroid. For elements with Z of 50 or more, the energy of K-x rays exceeds 25 keV. The K-x rays of lighter elements and all L-x rays are of lower energy and generally are not suitable for external measurements. These lower-energy radiations introduce measurement problems similar to those encountered with particles.

EC decay results frequently in a daughter nucleus that is in an excited or metastable state. Thus γ rays (or conversion electrons) may also be emitted. This is called (EC, γ) decay. Figure 3-6 shows a decay scheme for ^{125}I, an (EC, γ) radionuclide finding application

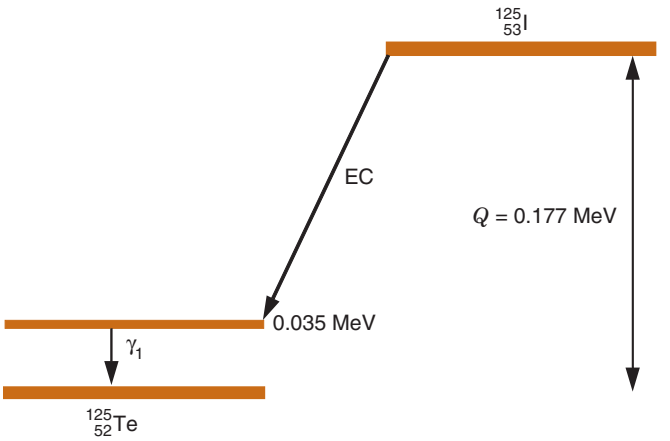


FIGURE 3-6 Decay scheme diagram for ^{125}I, an (EC, γ) emitter.

in radioimmunoassay studies. Note that EC decay is "to the left" because EC *decreases* the atomic number by one. Medically important EC and (EC, γ) radionuclides listed in Appendix C include ^{57}Co, ^{67}Ga, ^{111}In, ^{123}I, ^{125}I, and ^{201}Tl.

G. POSITRON (β^+) AND (β^+, γ) DECAY

In radioactive decay by positron emission, a proton in the nucleus is transformed into a neutron and a positively charged electron. The positively charged electron—or *positron* (β^+)—and a neutrino are ejected from the nucleus. Schematically, the process is:

$$p^+ \rightarrow n + e^+ + \nu + \text{energy} \qquad (3\text{-}6)$$

A positron is the antiparticle of an ordinary electron. After ejection from the nucleus, it loses its kinetic energy in collisions with atoms of the surrounding matter and comes to rest, usually within a few millimeters of the site of its origin in body tissues. More accurately, the positron and an electron momentarily form an "atom" called *positronium*, which has the positron as its "nucleus" and a lifetime of approximately 10^{-10} sec. The positron then combines with the negative electron in an *annihilation reaction*, in which their masses are converted into energy (see Fig. 3-7). The mass-energy equivalent of each particle is 0.511 MeV. This energy appears in the form of two 0.511-MeV *annihilation photons,** which leave the site of the annihilation event in nearly exact opposite directions (180 degrees apart).

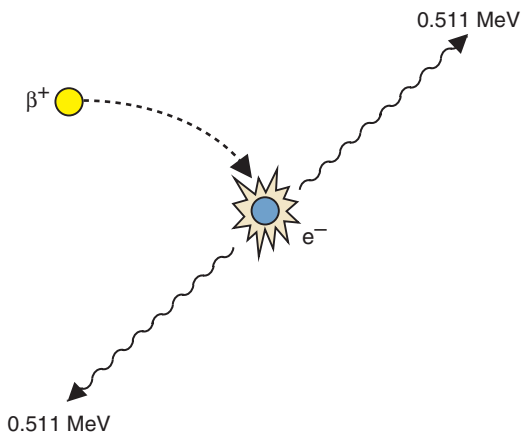


FIGURE 3-7 Schematic representation of mutual-annihilation reaction between a positron (β^+) and an ordinary electron. A pair of 0.511-MeV annihilation photons are emitted "back-to-back" at 180 degrees to each other.

The "back-to-back" emission of annihilation photons is required for conservation of momentum for a stationary electron-positron pair. However, because both particles actually are moving, the annihilation photons may be emitted in directions slightly off from the ideal by perhaps a few tenths of a degree. The effects of this on the ability to localize positron-emitting radionuclides for imaging purpose are discussed in Chapter 18, Section A.4.

Energy "bookkeeping" is somewhat more complicated for β^+ decay than for some of the previously discussed decay modes. There is a minimum transition energy requirement of 1.022 MeV before β^+ decay can occur. This requirement may be understood by evaluating the difference between the atomic mass of the parent and the daughter atom (including the orbital electrons). In β^+ decay, a positron is ejected from the nucleus, and because β^+ decay reduces the atomic number by one, the daughter atom also has an excess electron that it releases to reach its ground state. Thus two particles are emitted from the atom during β^+ decay, and because the rest-mass energy of an electron or a positron is 511 keV, a total transition energy of 1.022 MeV is required. Note that no such requirement is present for β^- decay, because the daughter atom must take up an electron from the environment to become neutral, thereby compensating for the electron released during β^- decay.

In β^+ decay, the excess transition energy above 1.022 MeV is shared between the positron (kinetic energy) and the neutrino. The positron energy spectrum is similar to that observed for β^- particles (see Fig. 3-2). The average β^+ energy also is denoted by $\bar{E}_\beta$ and again is approximately $\bar{E}_\beta \approx (1/3)E_\beta^{max}$, in which E_β^{max} is the transition energy minus 1.022 MeV.

In standard notation, β^+ decay is represented as

$$^{A}_{Z}X \xrightarrow{\beta^+} {}^{A}_{Z-1}Y \qquad (3\text{-}7)$$

It is another isobaric decay mode, with a transmutation of elements. Figure 3-8 shows

*Although the photons produced when the positron and an electron undergo annihilation are not of nuclear origin, they sometimes are called *annihilation γ rays*. This terminology may be used in some instances in this book.

a decay scheme for ^{15}O, a β^+ emitter of medical interest. Decay is "to the left" because atomic number *decreases* by one. The vertical line represents the minimum transition energy requirement for β^+ decay (1.022 MeV). The remaining energy (1.7 MeV) is E_β^{max}. With some radionuclides, β^+ emission may leave the daughter nucleus in an excited state, and thus additional γ rays may also be emitted [(β^+, γ) decay].

Positron emitters are useful in nuclear medicine because two photons are generated per nuclear decay event. Furthermore, the precise directional relationship between the annihilation photons permits the use of novel "coincidence-counting" techniques (see Chapter 18). Medically important pure β^+ radionuclides listed in Appendix C include ^{13}N and ^{15}O.

H. COMPETITIVE β^+ AND EC DECAY

Positron emission and EC have the same effect on the parent nucleus. Both are isobaric decay modes that decrease atomic number by one. They are alternative means for reaching the same endpoint (see Equations 3-5 and 3-7, and Figs. 3-6 and 3-8). Among the radioactive nuclides, one finds that β^+ decay occurs more frequently among lighter elements, whereas EC is more frequent among heavier elements, because in heavy elements orbital electrons tend to be closer to the nucleus and are more easily captured.

There also are radionuclides that can decay by either mode. An example is ^{18}F, the decay scheme for which is shown in Figure 3-9. For this radionuclide, 3% of the nuclei decay by EC and 97% decay by β^+ emission. Radionuclides of medical interest that undergo competitive (β^+, EC) decay listed in Appendix C include ^{11}C and ^{18}F.

I. DECAY BY α EMISSION AND BY NUCLEAR FISSION

Radionuclides that decay by α-particle emission or by nuclear fission are of relatively little importance for direct usage as tracers in nuclear medicine but are described here for the sake of completeness. Both of these decay modes occur primarily among very heavy elements that are of little interest as physiologic tracers. As well, they are highly energetic and tend to be associated with relatively large radiation doses (see Table 22-1).

In decay by α-particle emission, the nucleus ejects an α particle, which consists of two neutrons and two protons (essentially a ^4_2He nucleus). In standard notation this is represented as:

$$^{A}_{Z}X \xrightarrow{\alpha} {}^{A-4}_{Z-2}Y \qquad (3\text{-}8)$$

The α particle is emitted with kinetic energy usually between 4 and 8 MeV. Although quite energetic, α particles have *very* short ranges

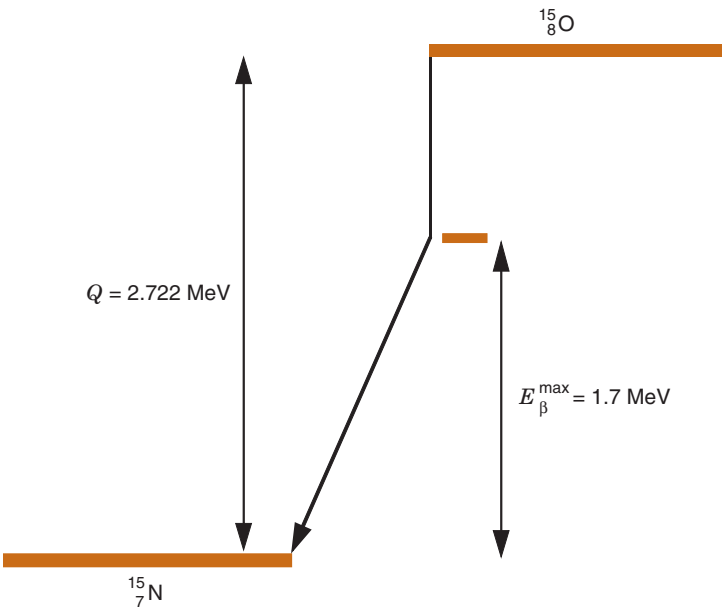


FIGURE 3-8 Decay scheme diagram for ^{15}O, a β^+ emitter. E_β^{max} is Q, the transition energy, minus 1.022 MeV, the minimum transition energy for β^+ decay.

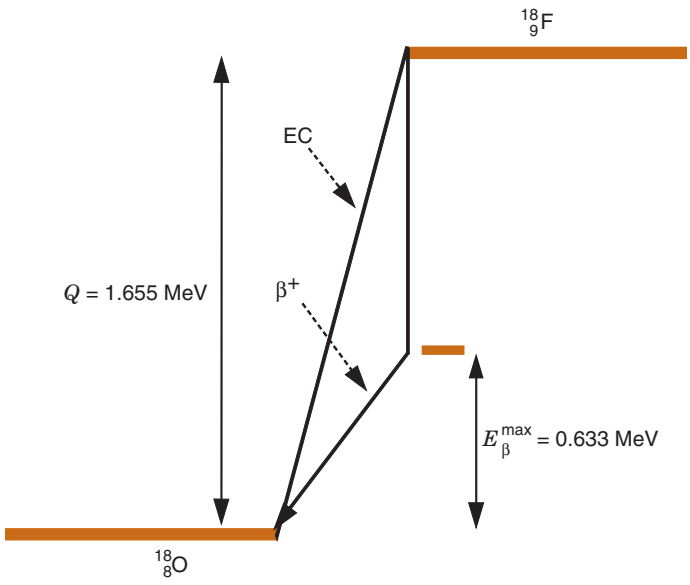


FIGURE 3-9 Decay scheme diagram for ^{18}F, which decays by both electron capture and β^+ emission competitively.

in solid materials, for example, approximately 0.03 mm in body tissues. Thus they present very difficult detection and measurement problems.

Decay by α-particle emission results in a transmutation of elements, but it is not isobaric. Atomic mass is decreased by 4; therefore this process is common among very heavy elements that must lose mass to achieve nuclear stability. Heavy, naturally occurring radionuclides such as ^{238}U and its daughter products undergo a series of decays involving α-particle and β^--particle emission to transform into lighter, more stable nuclides. Figure 3-10 illustrates the "decay series" of $^{238}\text{U} \rightarrow {}^{206}\text{Pb}$. The radionuclide ^{226}Ra in this series is of some medical interest, having been used at one time in encapsulated form for implantation into tumors for radiation therapy. The ubiquitous, naturally occurring ^{222}Rn also is produced in this series. Note that there are "branching points" in the series where either

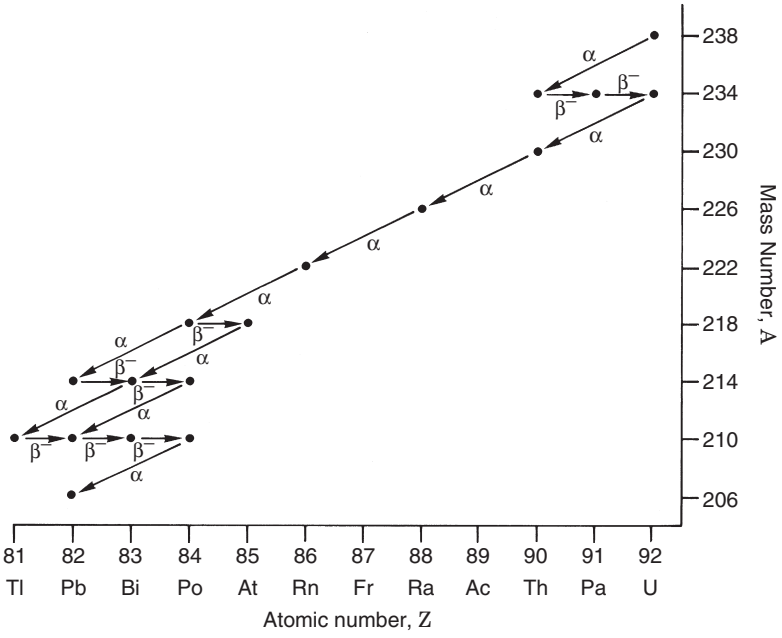


FIGURE 3-10 Illustration of series decay, starting from ^{238}U and ending with stable ^{206}Pb. (*Adapted from Hendee WR:* Medical Radiation Physics. *Chicago, 1970, Year Book Publishers Inc., p 501.*)

α or β^- emission may occur. Only every fourth atomic number value appears in this series because α emission results in atomic number differences of four units. The $^{238}U \rightarrow {}^{206}Pb$ series is called the "4n + 2" series. Two others are $^{235}U \rightarrow {}^{207}Pb$ (4n + 3) and $^{232}Th \rightarrow {}^{208}Pb$ (4n). These three series are found in nature because in each case the parent is a very long-lived radionuclide (half-lives ~ 10^8 to 10^{10} yr) and small amounts remain from the creation of the elements. The fourth series, 4n + 1, is not found naturally because all its members have much shorter lifetimes and have disappeared from nature.

An (α, γ) radionuclide of interest in nuclear medicine is ^{241}Am. It is used in encapsulated form as a source of 60-keV γ rays for instrument calibration and testing.

Nuclear fission is the spontaneous fragmentation of a very heavy nucleus into two lighter nuclei. In the process a few (two or three) *fission neutrons* also are ejected. The distribution of nuclear mass between the two product nuclei varies from one decay to the next. Typically it is split in approximately a 60:40 ratio. The energy released is very large, often amounting to hundreds of MeV per nuclear fission, and is imparted primarily as kinetic energy to the recoiling nuclear fragments (*fission fragments*) and the ejected neutrons. Nuclear fission is the source of energy from nuclear reactors. More precisely, the kinetic energy of the emitted particles is converted into heat in the surrounding medium, where it is used to create steam for driving turbines and other uses. The fission process is of interest in nuclear medicine because the fission fragment nuclei usually are radioactive and, if chemically separable from the other products, can be used as medical tracers. Also, the neutrons are used to produce radioactive materials by neutron activation, as discussed in Chapter 5, Section A.3. The parent fission nuclides themselves are of no use as tracers in nuclear medicine.

J. DECAY MODES AND THE LINE OF STABILITY

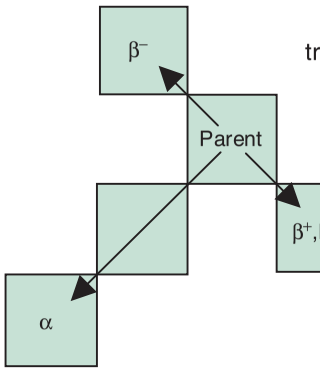
In Chapter 2, Section D.7, it was noted that on a graph of neutron versus proton numbers the stable nuclides tend to be clustered about an imaginary line called the *line of stability* (see Fig. 2-9). Nuclides lying off the line of stability generally are radioactive. The type of radioactive decay that occurs usually is such as to move the nucleus closer to this line. A radionuclide that is proton deficient (above the line) usually decays β^- emission, because this transforms a neutron into a proton, moving the nucleus closer to the line of stability. A neutron-deficient radionuclide (below the line) usually decays by EC or β^+ emission, because these modes transform a proton into a neutron. Heavy nuclides frequently decay by α emission or by fission, because these are modes that reduce mass number.

It also is worth noting that β^-, β^+, and EC decay all can transform an "odd-odd" nucleus into an "even-even" nucleus. As noted in Chapter 2, Section D.7 even-even nuclei are relatively stable because of pairing of alike particles within the nucleus. There are in fact a few odd-odd nuclides lying on or near the line of stability that can decay either by β^- emission or by EC and β^+ emission. An example is ^{40}K (89% β^-, 11% EC or β^+). In this example, the instability created by odd numbers of protons and neutrons is sufficient to cause decay in both directions *away* from the line of stability; however, this is the exception rather than the rule.

K. SOURCES OF INFORMATION ON RADIONUCLIDES

There are several sources of information providing useful summaries of the properties of radionuclides. One is a chart of the nuclides, a portion of which is shown in Figure 3-11. Every stable or radioactive nuclide is assigned a square on the diagram. Isotopes occupy horizontal rows and isotones occupy vertical columns. Isobars fall along descending 45-degree lines. Basic properties of each nuclide are listed in the boxes. Also shown in Figure 3-11 is a diagram indicating the transformations that occur for various decay modes. A chart of the nuclides is particularly useful for tracing through a radioactive series.

Perhaps the most useful sources of data for radionuclides of interest in nuclear medicine are the Medical Internal Radiation Dosimetry (MIRD) publications, compiled by the MIRD Committee of the Society of Nuclear Medicine.[1] Decay data for some of the radionuclides commonly encountered in nuclear medicine are presented in Appendix C. Also presented are basic data for internal dosimetry, which will be discussed in Chapter 22.



Radioactive transformations

Chart of the Nuclides (extract)

		42	44	46	48	50	52	54	56
47	Ag			Ag94 0.42 s	Ag95 2.0 s	Ag96 5.1 s	Ag97 19 s	Ag98 47 s	Ag99 11 s | 2.1 m	Ag100 2.3 m | 2.0 m	Ag101 3.1 s | 11.1 m	Ag102 7.8 m | 13 m	Ag103 5.7 s | 66 m	Ag104 33 m | 69 m
46	Pd				Pd94 9 s	Pd95 13.4 s	Pd96 2.03 m	Pd97 3.1 m	Pd98 18 m	Pd99 21.4 m	Pd100 3.6 d	Pd101 8.4 h	**Pd102** 1.02	Pd103 16.97 d
45	Rh					Rh94 26 s | 1.2 m	Rh95 1.96 m | 5 m	Rh96 1.5 m | 9.9 m	Rh97 46 m | 31 m	Rh98 3.5 m | 8.6 m	Rh99 4.7 h | 16.1 d	Rh100 4.7 m | 20.8 h	Rh101 4.34 d | 3.3 y	Rh102 206 d | 2.9 y
44	Ru			Ru90 11 s	Ru91 9 s	Ru92 3.7 m	Ru93 10.8 s | 1 m	Ru94 52 m	Ru95 1.64 h	**Ru96** 5.54	Ru97 2.89 d	**Ru98** 1.86	**Ru99** 12.7	**Ru100** 12.6	**Ru101** 17.1
43	Tc			Tc89 13 s | 13 s	Tc90 49.2 s | 8.3 s	Tc91 3.3 m | 3.1 m	Tc92 4.2 m	Tc93 43 m | 2.8 h	Tc94 52 m | 4.9 h	Tc95 61 d | 20 h	Tc96 52 m | 4.3 d	Tc97 90 d | 2.6E6y	Tc98 4.2E6 y	Tc99 6 h | 2.1E5y	Tc100 15.8 s
42	Mo	Mo86 20 s	Mo87 14 s	Mo88 8.0 m	Mo89 0.2 s | 2.2 m	Mo90 5.7 h	Mo91 1.1 m | 15.5 m	**Mo92** 14.84	Mo93 6.9 h | 3.5E3y	**Mo94** 9.25	**Mo95** 15.92	**Mo96** 16.68	**Mo97** 9.55	**Mo98** 24.13	Mo99 65.9 h
41	Nb	Nb83 4.1 s	Nb84 12 s	Nb85 21 s	Nb86 56 s | 1.5 m	Nb87 3.7 m | 2.6 m	Nb88 7.7 m | 14.4 m	Nb89 2 h | 1.1 h	Nb90 19 s | 14.6 h	Nb91 62 d | 7E2 y	Nb92 10.d | 3.7E7y	**Nb93** 6.1y | 100	Nb94 6.2 m | 2.4E4y	Nb95 3.6 d | 35 d	Nb96 23.4 h	Nb97 54 s | 74 m	Nb98 51 m | 2.8 s

FIGURE 3-11 Portion of a chart of the nuclides. *Vertical axis* = atomic number; *horizontal axis* = neutron number. Also listed are half-lives of radioactive nuclides (see Chapter 4, Section B.2). Stable nuclides are indicated in **bold** font. Values listed for these nuclides indicate their percent natural abundance. Half-lives of metastable states are listed on the left, where applicable.

REFERENCE

1. Eckerman KF, Endo A: MIRD: Radionuclide Data and Decay Schemes, New York, 2008, Society of Nuclear Medicine.

BIBLIOGRAPHY

A comprehensive source of radionuclide data can be found at the National Nuclear Data Center [accessed July 6, 2011]. Available at http://www.nndc.bnl.gov/.