Physics in Nuclear Medicine

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Modes of Radioactive Decay

Radioactive decay is a process in which an unstable nucleus transforms into a more stable one by emitting particles and/or photons and releasing nuclear energy. 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 release of nuclear energy. The energy released in a decay event is called the *transition energy,* sometimes designated Q. Most of this energy is imparted to emitted particles and photons, with a small (usually insignificant) fraction being imparted to the recoiling nucleus. The source of the energy released is a conversion of mass into energy. If all of the products of a particular decay event were gathered up and weighed, they would be found to weigh less than the original radioactive atom. 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—e.g., ^{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 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, a naturally occurring stable nuclide, and ^{131}I has the same radioactive characteristics whether it exists as iodide ion (I^-) or incorporated into a 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 atomic mass differences. Since 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—e.g., ^{12}C versus ^{14}C, ^{3}H versus ^{1}H. While they are important in some experiments, such as measurements of chemical bond strengths, they are, 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

$$n \rightarrow p^+ + e^- + \nu + \text{energy} \qquad (2-1)$$

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 *beta particle* (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

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

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—i.e., the parent and daughter are isobars.

Radioactive decay processes are often represented by a *decay scheme*. Figure 2–1 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, i.e., transition energy, for the decay process ($Q = 0.156$ MeV for ^{14}C).

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 2–2 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 of the energy ($E_\beta \approx E_\beta^{max}$). The *average* energy of the β^- particle is denoted by $\overline{E_\beta}$. This varies from one radionuclide to the next but

†Actually in β^- emission an antineutrino, $\bar{\nu}$, is emitted, whereas in β^+ emission and electron capture, a neutrino, ν, is emitted. For simplicity, no distinction will be made in this text.

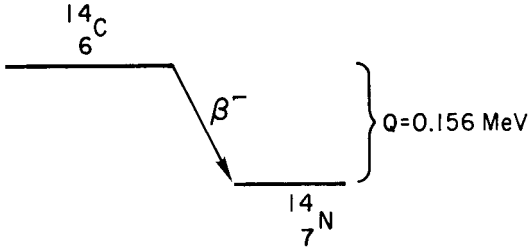


Fig. 2–1. Decay scheme diagram for ^{14}C, a β^- emitter. Q is the transition energy.

has a characteristic value for any given radionuclide. Typically, $\overline{E_\beta} \approx \frac{1}{3}E_\beta^{max}$. For ^{14}C, $E_\beta = 0.0493$ MeV ($0.32E_\beta^{max}$).

Beta particles themselves 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 (Chapter 8, Section B.2). For example, the thickness is at most only a few millimeters of 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 are also 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 4.

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

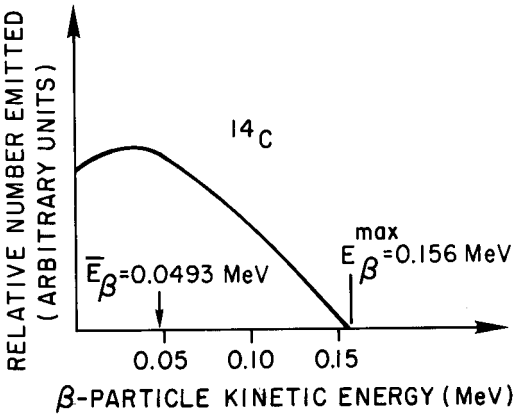


Fig. 2–2. Energy spectrum (number emitted versus energy) for β particles emitted by ^{14}C. Maximum β^- particle energy E_β^{max} is Q, the transition energy (Figure 2–1). Average energy $\overline{E}_\beta$ is 0.0493 MeV, about $\frac{1}{3}E_\beta^{max}$.

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 (Chapter 1, Section D.5). This sequential decay process is called (β^-, γ) decay. In standard nuclear notation, it may be represented as

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

Note that γ emission does not result in a transmutation.

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 2–3 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 relative probability values that are characteristic of the particular radionuclide. For example, in ^{133}Xe decay (Figure 2–3) 98.3 percent 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. Only a very small number of the other β particles and γ rays of other energies are emitted. The data presented in Appendix B 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 discrete series of energy

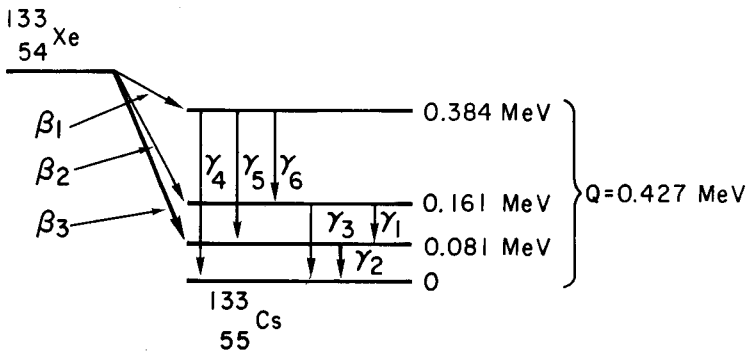


Fig. 2–3. Decay scheme diagram for ^{133}Xe, a (β^-,γ) emitter. More than one γ ray may be emitted per disintegrating nucleus. Heavier lines indicate most probable decay modes.

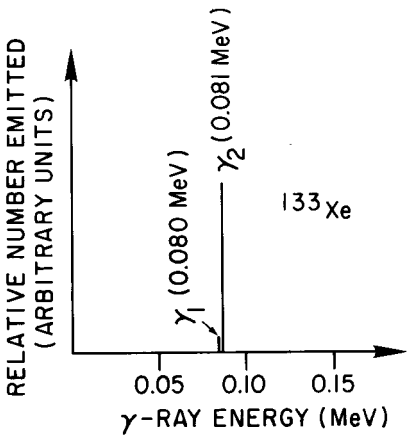


Fig. 2–4. Emission spectrum for 0.080 and 0.081 MeV γ rays emitted in the decay of ^{133}Xe (γ_1 and γ_2 in Figure 2–3; higher-energy emissions omitted). Compare with Figure 2–2 for β particles.

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 (Figure 2–4). 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.

Gamma rays are much more penetrating than β^- particles. Therefore 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 (β^-,γ) radionuclides of medical interest listed in Appendix B include ^{131}I and ^{133}Xe.

E. ISOMERIC TRANSITION (IT) AND INTERNAL CONVERSION (IC).

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 state by the emission of a γ ray is called an *isomeric transition* (Chapter 1, 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 that is especially frequent among metastable states is decay by internal conversion. In this process, the nucleus decays by 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

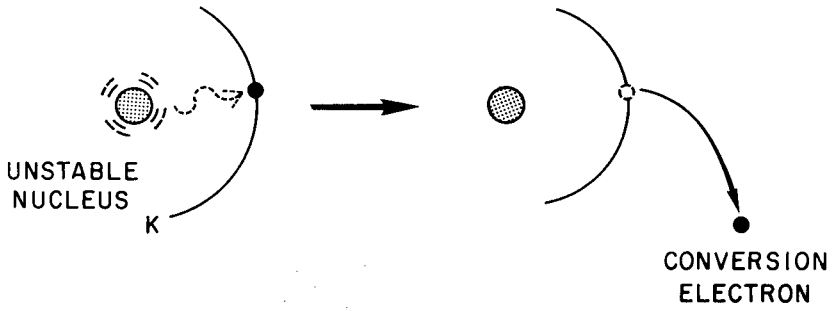


Fig. 2–5. Schematic representation of internal conversion involving a K shell electron. Unstable nucleus transfers its energy to an orbital electron rather than emitting a γ ray. Kinetic energy of conversion electron is γ-ray energy minus electron binding energy ($E_\gamma - K_B$).

electron (Figure 2–5). 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 is subsequently filled by an outer shell electron, with the emission of characteristic x rays or Auger electrons (Chapter 1, Section C.3).

Whether a γ ray or a conversion electron is emitted is a matter of probabilities, which 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 $\alpha_K = e/\gamma$ for K shell conversion electrons emitted, etc.).

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.

Metastable radionuclides are of great importance in nuclear medicine. Because of their relatively long lifetimes, it 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" (Chapter 7, Section E). Metastable nuclides always emit a certain number of conversion electrons, and thus they are not really "pure" γ-ray emitters; however, the ratio of photons to electrons emitted is greater usually 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 B is ^{99m}Tc. Technetium-99m is currently by far the most popular radionuclide for nuclear medicine imaging studies.

F. ELECTRON CAPTURE (EC) AND (EC,γ) DECAY

Electron capture 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:

$$p^+ + e^- \rightarrow n + \nu + \text{energy} \qquad (2\text{–}4)$$

The neutrino is emitted from the nucleus and carries away some of the transition energy. Additional 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, i.e., 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.

Electron capture decay may be represented as

$$^{A}_{Z}X \xrightarrow{EC} {}^{A}_{Z-1}Y \qquad (2\text{–}5)$$

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 electron capture 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, e.g., the thyroid. For elements with $Z \geq 50$, 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 β^- particles.

Electron capture 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 2–6 shows a decay scheme for

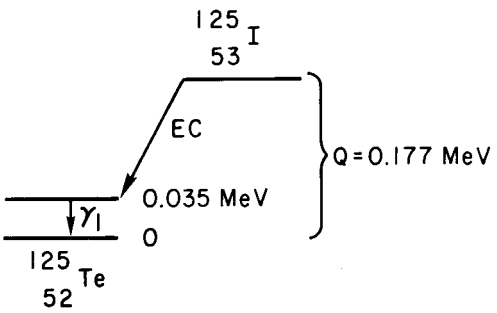


Fig. 2–6. Decay scheme diagram for ^{125}I, an (EC,γ) emitter.

^{125}I, an (EC,γ) radionuclide finding application in thyroid and radioimmunoassay studies. Note that EC decay is "to the left" because electron capture *decreases* the atomic number by one. Medically important EC and (EC,γ) radionuclides listed in Appendix B include ^{67}Ga, ^{111}In, ^{123}I, and ^{125}I.

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

$$p^+ \rightarrow n + e^+ + \nu + \text{energy} \qquad (2\text{–}6)$$

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. This occurs within about 10^{-9} sec. The positron then combines with an ordinary electron in an *annihilation reaction,* in which its mass and that of the ordinary electron are converted into energy (Figure 2–7). 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 in exact opposite directions (180° apart). Thus decay by β^+ emission ultimately results in the production of two 0.511 MeV photons.

Energy "bookkeeping" is somewhat more complicated in β^+ decay than in some of the previously discussed decay modes. The transition energy is divided among the kinetic energy of the positron, the neutrino, and the annihilation photons ($2 \times 0.511 = 1.022$ MeV). Thus there is a minimum transition

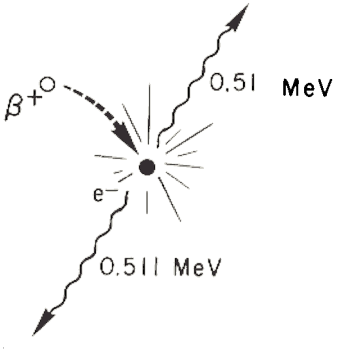


Fig. 2–7. Schematic representation of mutual annihilation reaction between a positron (β^+) and an ordinary electron. A pair of 0.511 MeV annihilation photons are emitted, "back to back" at 180° to each other.

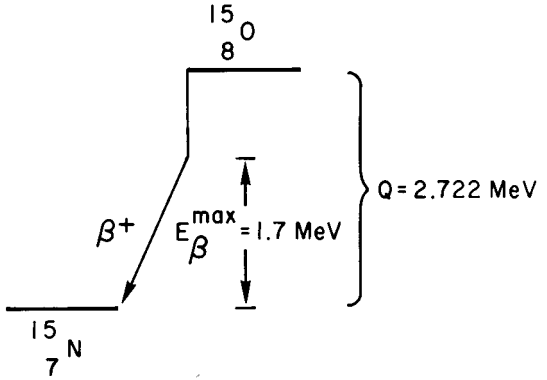


Fig. 2–8. Decay scheme diagram for ^{15}O, a β^+ emitter. E_β^{max} is Q, the transition energy, minus 1.022 MeV, the energy of the annihilation photons.

energy requirement of 1.022 MeV before β^+ decay can occur. 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 (Figure 2–2). The average β^+ energy also is denoted by $\overline{E_\beta}$ and again is approximately $\frac{1}{3}E_\beta^{max}$, where E_β^{max} is the transition energy minus 1.022 MeV.

In standard notation, β^+ decay is represented as

$$ {}_Z^AX \xrightarrow{\beta^+} + {}_{Z-1}^AY \tag{2–7} $$

It is another isobaric decay mode, with a transmutation of elements. Figure 2–8 shows 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 energy of the annihilation photons (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. The exact directional relationship between the annihilation photons is also useful because it permits the use of novel "coincidence counting" techniques (Chapter 17, Section D.3). Medically important β^+ radionuclides listed in Appendix B include ^{11}C, ^{13}N, and ^{15}O.

H. COMPETITIVE β^+ AND EC DECAY

Positron emission and electron capture 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 (Equations 2–5 and

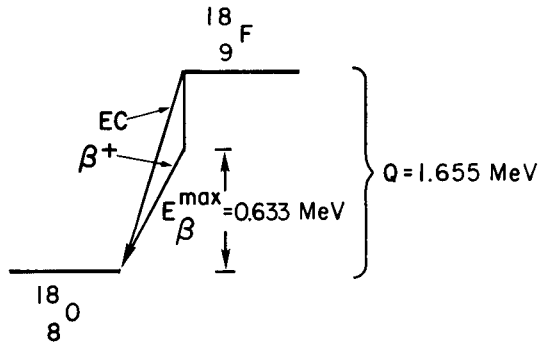


Fig. 2–9. Decay scheme diagram for ^{18}F, which decays by both EC and β^+ emission competitively.

2–7, Figures 2–6 and 2–8). Among the radioactive nuclides, one finds that β^+ decay occurs more frequently among lighter elements (assuming the minimum 1.022 MeV transition energy requirement is met), whereas electron capture is more frequent among heavier elements, since in heavy elements orbital electrons tend to be closer to the nucleus and are more easily captured.

There are also radionuclides that can decay by either mode. An example is ^{18}F, the decay scheme for which is shown in Figure 2–9. For this radionuclide, 3 percent of the nuclei decay by (EC,γ) and 97 percent by (β^+,γ). Radionuclides of medical interest that undergo competitive (β^+,EC) decay listed in Appendix B include ^{18}F and ^{68}Ga.

J. DECAY BY α EMISSION AND BY NUCLEAR FISSION

Decay by α-particle emission and decay by nuclear fission are of relatively little importance in nuclear medicine but will be 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.

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

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

The α particle is emitted with kinetic energy usually between 4 and 8 MeV. Although quite energetic, α particles have *very* short ranges in solid materials—e.g., about 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 is is not isobaric. Atomic mass is decreased by four; therefore this process is

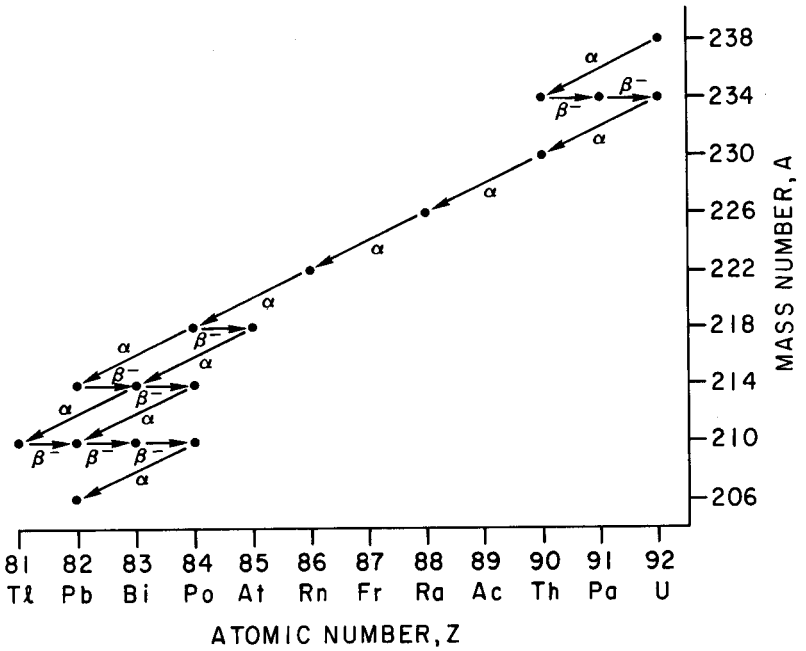


Fig. 2–10. Illustration of series decay, starting from ^{238}U and ending with stable ^{206}Pb. [Adapted with permission from Hendee WR Medical Radiation Physics. Chicago, Yearbook Medical Publishers, Inc., 1970, p. 50].

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 2–10 illustrates the "decay series" of $^{238}U \rightarrow {}^{206}Pb$. The radionuclide ^{226}Ra in this series is of some medical interest, used in encapsulated form for implantation into tumors in radiation therapy. Note that there are "branching points" in the series where either 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. 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 $\sim 10^8 - 10^{10}$ yr) and small amounts remain from the creation of the elements. The fourth series, 4n + 1, is not found naturally because all of 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 (Chapter 17, section E).

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 about 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. 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 may be used to produce radioactive materials by neutron activation, as discussed in Chapter 7, Section A.2. The fission nuclides themselves are of no use as tracers in nuclear medicine.

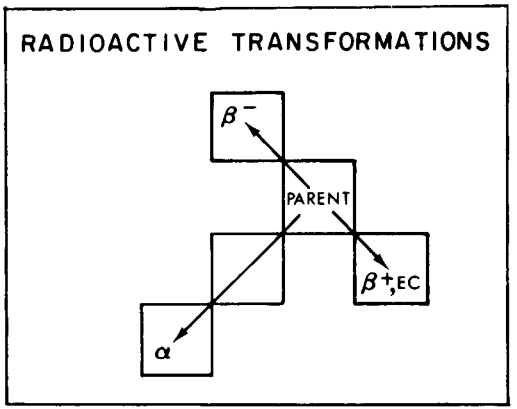
K. DECAY MODES AND THE LINE OF STABILITY

In Chapter 1, 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 (Figure 1–7). 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 the line. A radionuclide that is proton deficient (above the line) usually decays by β^- emission, since 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 electron capture or β^+ emission, since these modes transform a proton into a neutron. Heavy nuclides frequently decay by α emission or by fission, since these are modes that reduce mass number.

It is also worth noting the β^-, β^+, and EC decay all can transform an "odd–odd" nucleus into an "even–even" nucleus. There are in fact a few "odd–odd" nuclides lying on or near the line of stability that decay both by β^- emission and by electron capture and β^+ emission. An example is ^{40}K (89 percent β^-, 11 percent EC or β^+). In this case, the instability created by odd numbers of protons and neutrons is sufficient to cause decay in both directions *away* from the line of stability; this, however, is an exception rather than the rule.

L. 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 2–11. 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° lines. Basic properties of each nuclide are listed in the boxes. Also shown in Figure 2–11 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.



	92	94	96	98	100	102	104	106
82								Pb 207.2
81								Tl 204.37
80			Hg 200.59	Hg178 0.5s	Hg179 1.09s	Hg180 2.9s	Hg181 3.6s	Hg182 11s	Hg183 ~8.8s	Hg184 30.9s	Hg185 21s / 51s	Hg186 1.4m	Hg187 1.7m / 2.4m
79			Au 196.9665	Au177 1.3s	Au178 ~2.6s	Au179 7.5s		Au181 ~10s	Au182 21s	Au183 42s	Au184 52s	Au185 6.8m / 4.3m	Au186 ≤2m / 10.7m
78	Pt 195.09		Pt173 Short	Pt174 0.7s	Pt175 2.1s	Pt176 ~6.6s	Pt177 11s	Pt178 21s	Pt179 33s	Pt180 52s	Pt181 51s	Pt182 2.7m	Pt183 7m	Pt184	Pt185 33m / 1.1h
77	Ir 192.22	Ir171 1.0s	Ir172 ~1.7s	Ir173 3s	Ir174 4s	Ir175 ~4.5s	Ir176 8s	Ir177 21s	Ir178 ~0.5m		Ir180 1.5m	Ir181 5.0m	Ir182 15m	Ir183 58m	Ir184 3.0h
76	Os 190.2	Os170 7.1s	Os171 8s	Os172 19s	Os173 ~16s	Os174 ~45s		Os176 3.4m	Os177 ~3.5m	Os178 5m	Os179 8m	Os180 23m	Os181 27m / 105m	Os182 <3m / 21.5h	Os183 99% / 14h

Perhaps the most useful sources of data for radionuclides of interest in nuclear medicine are the MIRD publications, compiled by the Medical Internal Radiation Dosimetry committee of the Society of Nuclear Medicine.[1] Data from these tables for a few of the more important radionuclides are presented in Appendix B. Also presented are basic data for internal dosimetry, which will be discussed in Chapter 10.

REFERENCES

1. Dillman LT, Von der Lage FC: Radionuclide Decay Schemes and Nuclear Parameters for Use in Radiation-Dose Estimation. New York, The Society of Nuclear Medicine, 1975

Additional discussion of the modes of radioactive decay may be found in the following:

Hendee WR: Medical Radiation Physics (ed 2). Chicago, Yearbook Medical, 1979, Chap 2

Lapp RE, Andrews HL: Nuclear Radiation Physics (ed 4). Englewood Cliffs, N.J., Prentice-Hall, 1972, Chap 8

Rollo FD: Radioactivity and properties of nuclear radiation, in Rollo FD (ed): Nuclear Medicine Physics, Instrumentation, and Agents. St. Louis, C. V. Mosby, 1977, Chap 2

Fig. 2–11 (*left*). Portion of a chart of the nuclides. Vertical axis, atomic number; horizontal axis, neutron number. Also listed are atomic weights, thermal neutron capture cross sections (Chapter 7, Section D), half-lives of radioactive nuclides, and other data. [Reprinted by courtesy of Knolls Atomic Power Laboratory, Schenectady. Operated By The General Electric Company For The United States Department Of Energy Naval Reactors Branch.]