Section 3: Nuclear Stability and Radioactive Decay Modes

In a practical sense the definition of stability is a relative one. Time of observation is one factor. Sensitivity of detection devices is another. The stable nuclei are those near the peak of the binding energy curve, for which the neutron/proton combination or energy state does not change with time. Present upper limits on the measurement of nuclear lifetimes are about 10^{20} years. So from a kinetics sense, anything with a longer lifetime is considered to be stable. But it is possible for nuclei to be thermodynamically unstable, but with a lifetime so long we cannot detect it.

There are 266 nuclei that are considered to be stable. Every element up to and including bismuth (Z = 83) has at least one stable isotope, except technetium (Z = 43) and promethium (Z=61). These latter two elements do not exist on earth, but have been created in the laboratory and their atomic spectra are observed in young stars.

Radioactive nuclei are those that SPONTANEOUSLY alter their neutron/proton composition or energy state. As such, radioactivity is a first-order rate process , identical to unimolecular decay in chemical systems

$$A \rightarrow B + C$$

As described in Sec. 1, the rate of decay is characterized by a half-life, $t_{1/2}$, which is the time required for one-half the nuclei in a sample to disintegrate (decay), i.e. for a sample of N nuclei,

$$-dN/dt = \lambda N \text{ and } \quad t_{1/2} = 0.693/\lambda .$$

The kinetics of radioactive decay will be examined in more detail in a later section. There are many radioactive nuclei that occur on earth because their lifetimes are comparable to or longer than the age of the solar system, ~4.5 x 10^9 years. Most of these are associated with the decay of uranium and thorium isotopes and their daughter nuclei that are formed in the chain of decays that lead to the stable lead isotopes.

.

Most unstable nuclei undergo four types of radioactive decay, discussed more fully in Sections 9 – 12:

- Alpha decay (α) – emission of a ^{4}He nucleus

  $$^{222}Rn \rightarrow {}^{218}Po + {}^4He$$

- Beta decay ($\beta = e$) – decays involving an electron: conversion of a neutron into a proton (β^- emission) or conversion of a proton into a neutron (β^+ emission or electron capture on a neutron); for bookkeeping purposes, e signifies an atomic electron and β indicates the electron is of nuclear origin.

  Negatron (β^-) emission: $^{40}K \rightarrow {}^{40}Ca + \beta^- + \overline{\nu}$

  Electron capture: $^{40}K + e^- \rightarrow {}^{40}Ar + \nu$

  Positron (β^+) emission: $^{22}Na \rightarrow {}^{22}Ne + \beta^+ + \nu$

  The symbol ν stands for the neutrino, a massless, zero-charge particle that is always involved in beta decay

- Gamma decay (γ) – emission of a photon; gamma rays are high energy electromagnetic radiation originating from transitions in excited nuclei, whereas xrays, uv, visible and ir photons result from atomic and molecular transitions.

$$^{60}Co \rightarrow {}^{60}Co + \gamma$$

- Spontaneous fission (SF) – splitting of a heavy nucleus into two nearly equal mass fragments, usually accompanied nu the emission of neutrons.

$$^{235}U \rightarrow {}^{130}Sn + {}^{103}Mo + 2\,{}^{1}n$$

Beta and gamma decay occur for nuclei of all masses, while alpha decay is limited primarily to nuclei heavier than neodymium (Z=60) and spontaneous fission is limited to thorium (Z = 90) and above. Other decay modes have been observed, for example proton decay, neutron decay, and ^{14}C emission, but these are rare cases.

The uranium and thorium decay series account for a substantial fraction of the radioactivites that occur on earth. These decay chains are summarized below, where n is an integer:

$$^{238}_{92}U\ (4.5 \times 10^{9}y)\ \underset{6\beta^-}{\overset{8\alpha}{\rightarrow}}\ ^{206}_{82}Pb\,(24.1\%)\ ; \qquad A = 4n + 2$$

$$^{235}_{92}U\ (7.1 \times 10^{8}y)\ \underset{4\beta^-}{\overset{7\alpha}{\rightarrow}}\ ^{207}_{82}Pb\ (22.1\%); \qquad A = 4n + 3$$

$$^{232}_{90}Th\ (1.4 \times 10^{9}y)\ \underset{4\beta^-}{\overset{6\alpha}{\rightarrow}}\ ^{208}_{82}Pb\ (52.3\%); \qquad A = 4n$$

$$\text{EXTINCT:}\ ^{237}_{93}Np\ (2 \times 10^{6}y)\ \underset{4\beta^-}{\overset{7\alpha}{\rightarrow}}\ ^{209}Bi\ (100\%)\ ; \qquad A = 4n + 1$$

The neptunium decay series does not occur on earth because the lifetime of ^{237}Np is too short and it has decayed away long ago. Altogether there are 45 isotopes in the uranium-thorium decay chains. The detailed decay chain for ^{238}U is shown below:

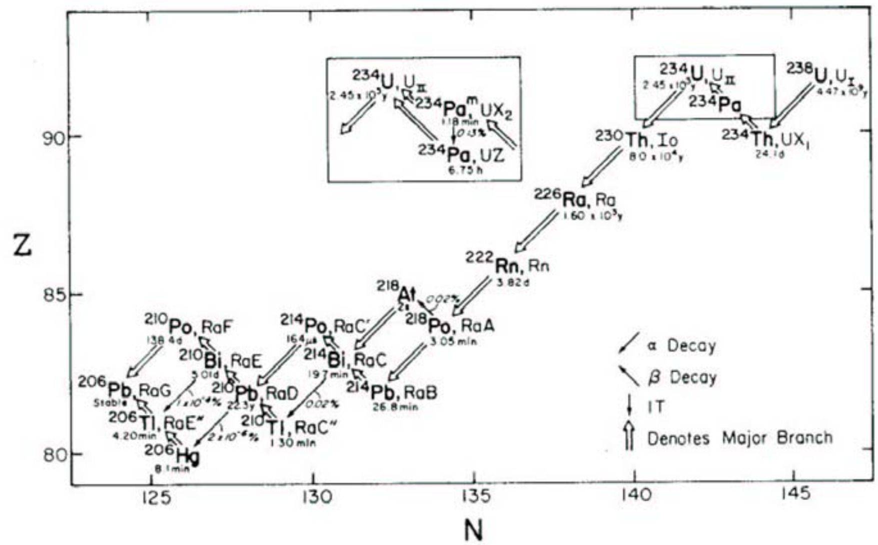

Fig. 3-1 The ^{238}U decay series showing alpha and beta decay paths.

In addition to the U-Th decay series, there are several additional radioactivites present on earth, listed in Table 3-1.

Table 3.1
Naturally occurring radioactive nuclei

Active Substance[a]	Type of Disintegration[b]	Half Life (y)	Isotopic Abundance (%)	Stable Disintegration Products
^{40}K	β^-, EC, β^+	1.28×10^9	0.0117	^{40}Ca, ^{40}Ar
^{87}Rb	β^-	4.8×10^{10}	27.83	^{87}Sr
^{113}Cd	β^-	9×10^{15}	12.2	^{113}In
^{115}In	β^-	5.1×10^{14}	95.7	^{115}Sn
^{138}La	EC, β^-	1.1×10^{11}	0.089	^{138}Ba, ^{138}Ce
^{144}Nd	α	2.1×10^{15}	23.8	^{140}Ce
^{147}Sm	α	1.06×10^{11}	15.1	^{143}Nd
^{148}Sm	α	8×10^{15}	11.3	^{144}Nd
^{152}Gd	α	1.1×10^{14}	0.20	^{148}Sm
^{176}Lu	β^-	3.6×10^{10}	2.61	^{176}Hf
^{174}Hf	α	2.0×10^{15}	0.16	^{170}Yb
^{187}Re	β^-	4×10^{10}	62.60	^{187}Os
^{190}Pt	α	6×10^{11}	0.013	^{186}Os
^{50}V	β^-, EC	6×10^{15} y	0.24	
^{186}Os	α	10^{15} y	1.59	

Most important among these is ^{40}K, which is the major source of radioactivity in our bodies (you can't avoid the alkali metals) and ^{87}Rb, which is one of the best chronometers for the age of the solar system.

Cosmic rays also bombard our earth's atmosphere, creating radioactive nuclei such as ^{3}H, ^{14}C and ^{7}Be, all of which have applications in tracing the chronology of our atmosphere and the history of civilization. And finally, there are the about 3000 isotopes that have been synthesized in accelerator laboratories, accounting for all the elements up to Z = 114, with tentative reports of elements up to Z = 118.

As will be discussed later, rates of nuclear decay are governed primarily by two factors:

(1) Energetics – a large Q-value usually favor rapid decay; i.e. short half-life, and
(2) Quantum structure – differences in spin and orbital angular momentum states can also lengthen the half-life.