MODES OF RADIOACTIVE DECAY

Most atoms found in nature are stable and do not emit particles or energy that change form over time. Some atoms, however, do not have stable nuclei. These atoms emit radiation in order to achieve a more stable configuration.

EO 2.1 DESCRIBE the following processes:

a.	**Alpha decay**	**d.**	**Electron capture**
b.	**Beta-minus decay**	**e.**	**Internal conversions**
c.	**Beta-plus decay**	**f.**	**Isomeric transitions**

EO 2.2 Given a Chart of the Nuclides, WRITE the radioactive decay chain for a nuclide.

EO 2.3 EXPLAIN why one or more gamma rays typically accompany particle emission.

EO 2.4 Given the stability curve on the Chart of the Nuclides, DETERMINE the type of radioactive decay that the nuclides in each region of the chart will typically undergo.

Stability of Nuclei

As mass numbers become larger, the ratio of neutrons to protons in the nucleus becomes larger for the stable nuclei. Non-stable nuclei may have an excess or deficiency of neutrons and undergo a transformation process known as beta (β) decay. Non-stable nuclei can also undergo a variety of other processes such as alpha (α) or neutron (n) decay. As a result of these decay processes, the final nucleus is in a more stable or more tightly bound configuration.

Natural Radioactivity

In 1896, the French physicist Becquerel discovered that crystals of a uranium salt emitted rays that were similar to x-rays in that they were highly penetrating, could affect a photographic plate, and induced electrical conductivity in gases. Becquerel's discovery was followed in 1898 by the identification of two other radioactive elements, polonium and radium, by Pierre and Marie Curie.

Heavy elements, such as uranium or thorium, and their unstable decay chain elements emit radiation in their naturally occurring state. Uranium and thorium, present since their creation at the beginning of geological time, have an extremely slow rate of decay. All naturally occurring nuclides with atomic numbers greater than 82 are radioactive.

Nuclear Decay

Whenever a nucleus can attain a more stable (i.e., more tightly bound) configuration by emitting radiation, a spontaneous disintegration process known as radioactive decay or nuclear decay may occur. In practice, this "radiation" may be electromagnetic radiation, particles, or both.

Detailed studies of radioactive decay and nuclear reaction processes have led to the formulation of useful conservation principles. The four principles of most interest in this module are discussed below.

Conservation of electric charge implies that charges are neither created nor destroyed. Single positive and negative charges may, however, neutralize each other. It is also possible for a neutral particle to produce one charge of each sign.

Conservation of mass number does not allow a net change in the number of nucleons. However, the conversion of a proton to a neutron and vice versa is allowed.

Conservation of mass and energy implies that the total of the kinetic energy and the energy equivalent of the mass in a system must be conserved in all decays and reactions. Mass can be converted to energy and energy can be converted to mass, but the sum of mass and energy must be constant.

Conservation of momentum is responsible for the distribution of the available kinetic energy among product nuclei, particles, and/or radiation. The total amount is the same before and after the reaction even though it may be distributed differently among entirely different nuclides and/or particles.

Alpha Decay (α)

Alpha decay is the emission of alpha particles (helium nuclei) which may be represented as either ${}^{4}_{2}\text{He}$ or ${}^{4}_{2}\alpha$. When an unstable nucleus ejects an alpha particle, the atomic number is reduced by 2 and the mass number decreased by 4. An example is uranium-234 which decays by the ejection of an alpha particle accompanied by the emission of a 0.068 MeV gamma.

$${}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\alpha + \gamma + \text{KE}$$

The combined kinetic energy of the daughter nucleus (Thorium-230) and the α particle is designated as KE. The sum of the KE and the gamma energy is equal to the difference in mass between the original nucleus (Uranium-234) and the final particles (equivalent to the binding energy released, since $\Delta m = BE$). The alpha particle will carry off as much as 98% of the kinetic energy and, in most cases, can be considered to carry off all the kinetic energy.

Beta Decay (β)

Beta decay is the emission of electrons of nuclear rather than orbital origin. These particles are electrons that have been expelled by excited nuclei and may have a charge of either sign.

If both energy and momentum are to be conserved, a third type of particle, the neutrino, ν, must be involved. The neutrino is associated with positive electron emission, and its antiparticle, the antineutrino, $\bar{\nu}$, is emitted with a negative electron. These uncharged particles have only the weakest interaction with matter, no mass, and travel at the speed of light. For all practical purposes, they pass through all materials with so few interactions that the energy they possess cannot be recovered. The neutrinos and antineutrinos are included here only because they carry a portion of the kinetic energy that would otherwise belong to the beta particle, and therefore, must be considered for energy and momentum to be conserved. They are normally ignored since they are not significant in the context of nuclear reactor applications.

Negative electron emission, represented as ${}^{0}_{-1}e$, ${}^{0}_{-1}\beta$, or simply as e^- or β^-, effectively converts a neutron to a proton, thus increasing the atomic number by one and leaving the mass number unchanged. This is a common mode of decay for nuclei with an excess of neutrons, such as fission fragments below and to the right of the neutron-proton stability curve (refer to Figure 6). An example of a typical beta minus-decay reaction is shown below.

$${}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

Positively charged electrons (beta-plus) are known as positrons. Except for sign, they are nearly identical to their negatively charged cousins. When a positron, represented as ${}^{0}_{+1}e$, ${}^{0}_{+1}\beta$, or simply as e^+ or β^+, is ejected from the nucleus, the atomic number is decreased by one and the mass number remains unchanged. A proton has been converted to a neutron. An example of a typical positron (beta-plus) decay is shown below.

$$ {}^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{+1}\beta + {}^{0}_{0}\nu $$

Electron Capture (EC, K-capture)

Nuclei having an excess of protons may capture an electron from one of the inner orbits which immediately combines with a proton in the nucleus to form a neutron. This process is called *electron capture* (EC). The electron is normally captured from the innermost orbit (the K-shell), and, consequently, this process is sometimes called K-capture. The following example depicts electron capture.

$$ {}^{7}_{4}Be + {}^{0}_{-1}e \rightarrow {}^{7}_{3}Li + {}^{0}_{0}\nu $$

A neutrino is formed at the same time that the neutron is formed, and energy carried off by it serves to conserve momentum. Any energy that is available due to the atomic mass of the product being appreciably less than that of the parent will appear as gamma radiation. Also, there will always be characteristic x-rays given off when an electron from one of the higher energy shells moves in to fill the vacancy in the K-shell. Electron capture is shown graphically in Figure 8.

Electron capture and positron emission result in the production of the same daughter product, and they exist as competing processes. For positron emission to occur, however, the mass of the daughter product must be less than the mass of the parent by an amount equal to at least twice the mass of an electron. This mass difference between the parent and daughter is necessary to account for two items present in the parent but not in the daughter. One item is the positron ejected from the nucleus of the parent. The other item is that the daughter product has one less orbital electron than the parent. If this requirement is not met, then orbital electron capture takes place exclusively.

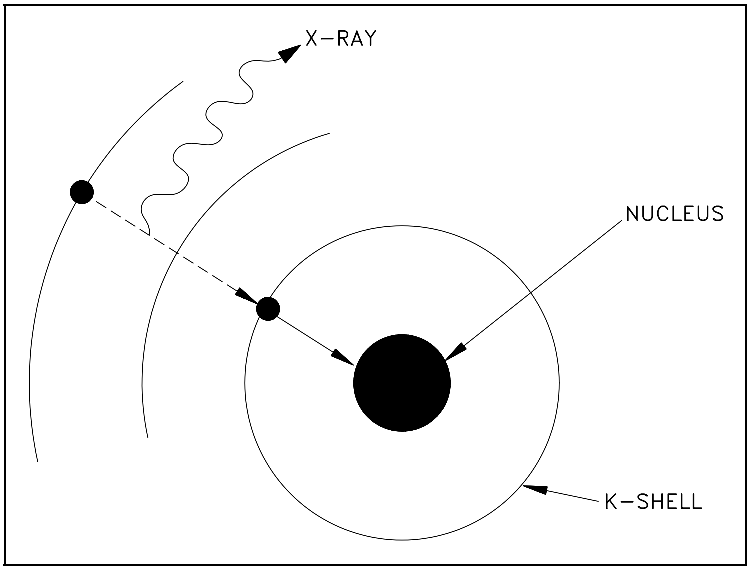

Figure 9 Orbital Electron Capture

Gamma Emission (γ)

Gamma radiation is a high-energy electromagnetic radiation that originates in the nucleus. It is emitted in the form of photons, discrete bundles of energy that have both wave and particle properties. Often a daughter nuclide is left in an excited state after a radioactive parent nucleus undergoes a transformation by alpha decay, beta decay, or electron capture. The nucleus will drop to the ground state by the emission of gamma radiation.

Internal Conversion

The usual method for an excited nucleus to go from the excited state to the ground state is by emission of gamma radiation. However, in some cases the gamma ray (photon) emerges from the nucleus only to interact with one of the innermost orbital electrons and, as a result, the energy of the photon is transferred to the electron. The gamma ray is then said to have undergone *internal conversion*. The conversion electron is ejected from the atom with kinetic energy equal to the gamma energy minus the binding energy of the orbital electron. An orbital electron then drops to a lower energy state to fill the vacancy, and this is accompanied by the emission of characteristic x-rays.

Isomers and Isomeric Transition

Isomeric transition commonly occurs immediately after particle emission; however, the nucleus may remain in an excited state for a measurable period of time before dropping to the ground state at its own characteristic rate. A nucleus that remains in such an excited state is known as a nuclear *isomer* because it differs in energy and behavior from other nuclei with the same atomic number and mass number. The decay of an excited nuclear isomer to a lower energy level is called an *isomeric transition*. It is also possible for the excited isomer to decay by some alternate means, for example, by beta emission.

An example of gamma emission accompanying particle emission is illustrated by the decay of nitrogen-16 below.

$$ {}^{16}_{7}\mathrm{N} \rightarrow \left({}^{16}_{8}\mathrm{O}\right)^{*} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu} $$

$$ \left({}^{16}_{8}\mathrm{O}\right)^{*} \rightarrow {}^{16}_{8}\mathrm{O} + {}^{0}_{0}\gamma $$

Decay Chains

When an unstable nucleus decays, the resulting daughter nucleus is not necessarily stable. The nucleus resulting from the decay of a parent is often itself unstable, and will undergo an additional decay. This is especially common among the larger nuclides.

It is possible to trace the steps of an unstable atom as it goes through multiple decays trying to achieve stability. The list of the original unstable nuclide, the nuclides that are involved as intermediate steps in the decay, and the final stable nuclide is known as the *decay chain*. One common method for stating the decay chain is to state each of the nuclides involved in the standard ${}^{A}_{Z}X$ format. Arrows are used between nuclides to indicate where decays occur, with the type of decay indicated above the arrow and the half-life below the arrow. The half-life for decay will be discussed in the next chapter.

Example:

> Write the decay chains for rubidium-91 and actinium-215. Continue the chains until a stable nuclide or a nuclide with a half-life greater than 1 x 10^6 years is reached.

Solution:

$${}^{91}_{37}\text{Rb} \xrightarrow[58.0\ \text{s}]{\beta^-} {}^{91}_{38}\text{Sr} \xrightarrow[9.5\ \text{hrs}]{\beta^-} {}^{91}_{39}\text{Y} \xrightarrow[58.5\ \text{d}]{\beta^-} {}^{91}_{40}\text{Zr}$$

$${}^{215}_{85}\text{At} \xrightarrow[0.10\ \text{ms}]{\alpha} {}^{211}_{83}\text{Bi} \xrightarrow[2.14\ \text{min}]{\alpha} {}^{207}_{81}\text{Tl} \xrightarrow[4.77\ \text{min}]{\beta^-} {}^{207}_{82}\text{Pb}$$

Predicting Type of Decay

Radioactive nuclides tend to decay in a way that results in a daughter nuclide that lies closer to the line of stability. Due to this, it is possible to predict the type of decay that a nuclide will undergo based on its location relative to the line of stability on the Chart of the Nuclides.

Figure 9 illustrates the type of decay nuclides in different regions of the chart will typically undergo. Nuclides that are below and to the right of the line of stability will usually undergo β^- decay. Nuclides that are above and to the left of the line of stability will usually undergo either β^+ decay or electron capture. Most nuclides that will undergo α decay are found in the upper right hand region of the chart. These are general rules that have many exceptions, especially in the region of the heavy nuclides.

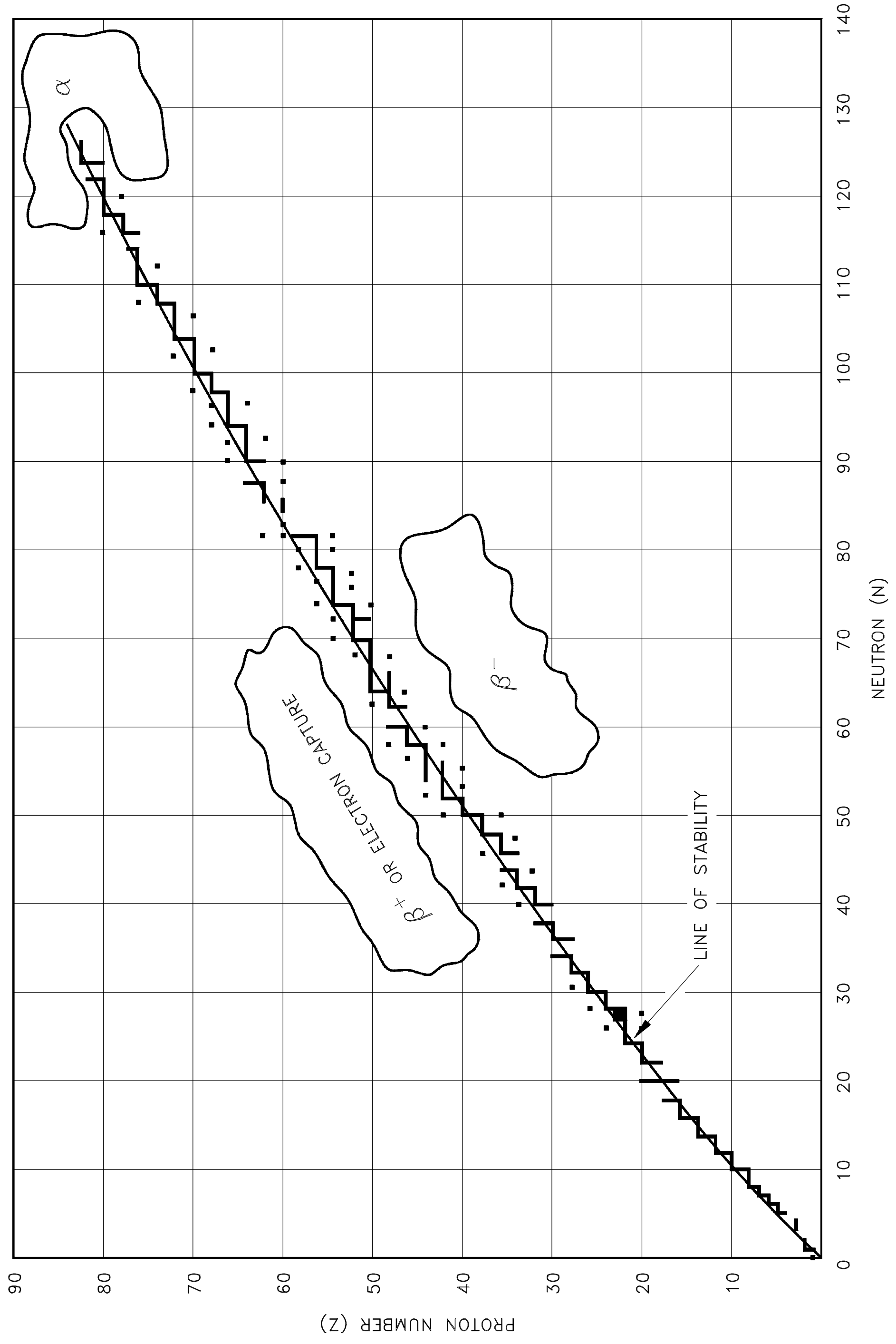

Figure 9 Types of Radioactive Decay Relative to the Line of Stability

Summary

The important information in this chapter is summarized below.

Modes of Radioactive Decay Summary

- Alpha decay is the emission of an alpha particle (2 protons and 2 neutrons) from an unstable nucleus. The daughter nuclide has an atomic number 2 less than the parent nuclide and a mass number 4 less than the parent nuclide. The daughter nucleus commonly releases its excitation energy by gamma emission.
- Beta-minus decay effectively converts a neutron to a proton and an electron, which is immediately ejected from the nucleus. The daughter nuclide has its atomic number increased by 1 and the same mass number compared to the parent.
- Beta-plus decay effectively converts a proton to a neutron and a positron, which is immediately ejected from the nucleus. The daughter nuclide has its atomic number decreased by 1 and the same mass number compared to the parent.
- In electron capture, the nucleus absorbs an electron from the innermost orbit. This electron combines with a proton to form a neutron.
- Internal conversion occurs when a gamma ray, emitted by the nucleus as it goes from the excited state to the ground state, interacts with one of the innermost electrons of the same atom. The electron is ejected from the atom.
- An isomeric transition is the decay of an excited nucleus to a lower-energy level by the emission of a gamma ray.
- Decay chains can be found by tracing the steps an unstable atom goes through as it tries to achieve stability.
- Many modes of radioactive decay result in a daughter nuclide that has an energy level above the ground state. This excitation energy is usually released immediately in the form of a gamma ray.
- The type of decay that a nuclide will typically undergo can be determined by its relationship to the line of stability on the Chart of the Nuclides. Nuclides that lie below and to the right of the line of stability will typically beta minus decay. Nuclides above and to the left of the line will typically either beta plus decay or electron capture. Most alpha emitters are found in the upper, right-hand corner of the chart.