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Chapter Four

(Nuclear Radiation)

(4-1) Nuclear Radiation

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.

1. 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.
2. 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.
3. 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.

4. 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 $^{4}_{2}He$ 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.

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

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 Δm=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. An example of a typical beta minus-decay reaction is shown below.

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

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.

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

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.

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.

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

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 (4-1).

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.

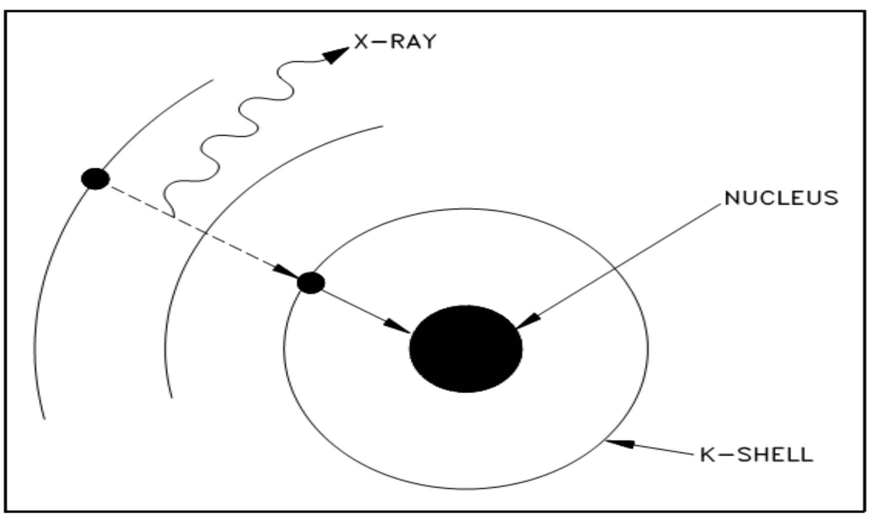


Figure (4-1): Orbital electron capture.

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.

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

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

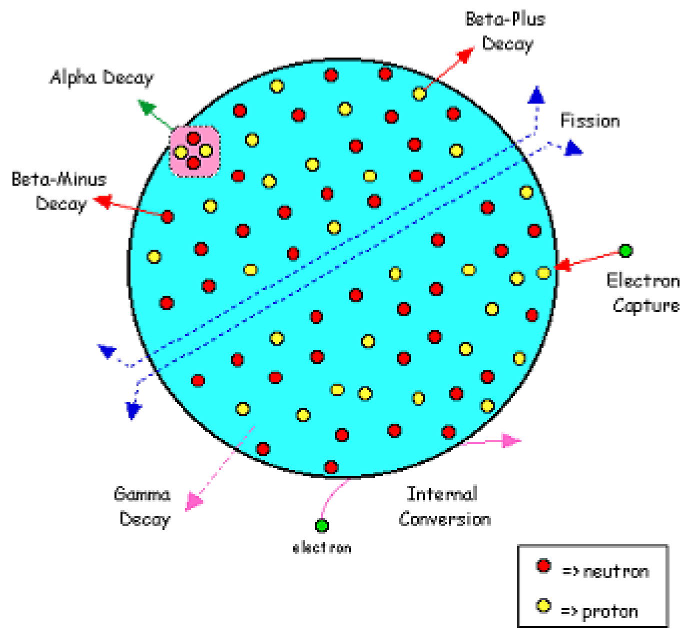
Another example of this type of decay is that of technetium-99m , which by the way is the most common radioisotope used for diagnostic purposes today in medicine. The reaction can be expressed as:

$$^{99m}_{43}\text{Tc} \rightarrow ^{99}_{43}\text{Tc} + \gamma$$

Here a nucleus of technetium-99 is in an excited state that is it has excess energy. The excited state in this case is called a metastable state and the nucleus is therefore called technetium-99m (m for metastable). The excited nucleus loses its excess energy by emitting a gamma-ray to become technetium-99.

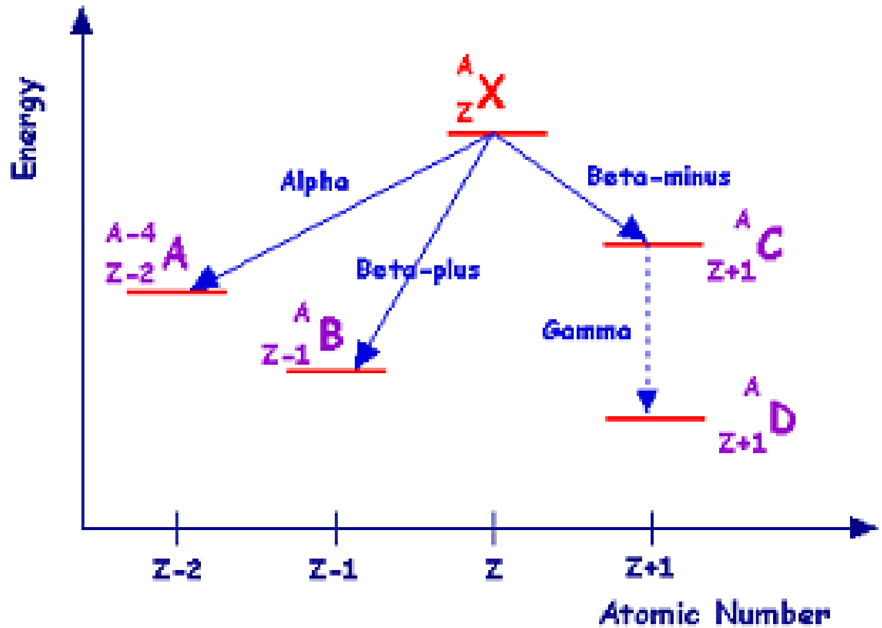
Spontaneous Fission

This is a very destructive process which occurs in some heavy nuclei which split into 2 or 3 fragments plus some neutrons. These fragments form new nuclei which are usually radioactive. Nuclear reactors exploit this phenomenon for the production of radioisotopes. It's also used for nuclear power generation and in nuclear weaponry. The process is not of great interest to us here and we will say no more about it for the time being.



Decay Schemes

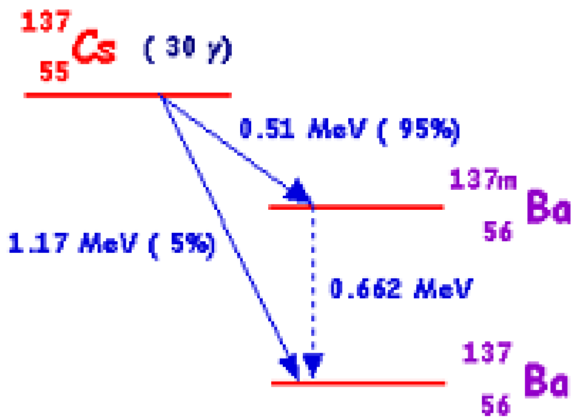
Decay schemes are widely used to give a visual representation of radioactive decay. The general method used for decay schemes is illustrated in the diagram below:



The energy is plotted on the vertical axis and atomic number on the horizontal axis-although these axes are rarely displayed in actual schemes. The isotope from which the scheme originates is displayed at the top - X in the case above. This isotope is referred to as the parent. The parent loses energy when it decays and hence the products of the decay referred to as daughters are plotted at a lower energy level.

The diagram illustrates the situation for common forms of radioactive decay. Alpha-decay is illustrated on the left where the mass number is reduced by 4 and the atomic number is reduced by 2 to produce daughter A. To its right the scheme for beta-plus decay is shown to produce daughter B. The situation for beta-minus decay followed by gamma-decay is shown on the right side of the diagram where daughters C and D respectively are produced.

For example, a scheme for a more complicated decay is that of caesium-137: This isotope can decay through two beta-minus processes. In one which occurs in 5% of disintegrations a beta-minus particle is emitted with energy of 1.17MeV to produce barium-137. In the second, which occurs more frequently (in the remaining 95% of disintegrations) a beta-minus particle of energy 0.51MeV is emitted to produce barium-137m, in other words a barium-137 nucleus in a metastable state. The barium-137m then decays via isomeric transition with the emission of a gamma-ray of energy 0.662MeV.



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 $1x10^6$ years is reached.

Solution:

$$^{91}_{37}Rb \underset{58.0\ s}{\overset{\beta^-}{\rightarrow}} {}^{91}_{38}Sr \underset{9.5\ hrs}{\overset{\beta^-}{\rightarrow}} {}^{91}_{39}Y \underset{58.5\ d}{\overset{\beta^-}{\rightarrow}} {}^{91}_{40}Zr$$

$$^{215}_{85}At \underset{0.10\ ms}{\overset{\alpha}{\rightarrow}} {}^{211}_{83}Bi \underset{2.14\ min}{\overset{\alpha}{\rightarrow}} {}^{207}_{81}Tl \underset{4.77\ min}{\overset{\beta^-}{\rightarrow}} {}^{207}_{82}Pb$$