Nuclear Physics

Decay Modes and Decay Rates

TABLE OF CONTENTS

INTRODUCTION

OBJECTIVES

1.0 RADIOACTIVE DECAY

1.1 ALPHA DECAY
1.2 BETA MINUS DECAY
1.3 GAMMA EMISSION
1.4 ELECTRON CAPTURE/BETA PLUS DECAY
1.5 NEUTRON EMISSION
1.6 SPONTANEOUS FISSION

2.0 ARTIFICIALLY PRODUCED RADIOACTIVE MATERIALS

3.0 DECAY RATES AND HALF LIVES

3.1 THE CURIE

4.0 SUMMARY
INTRODUCTION

We have defined radioactivity in the previous lesson as the spontaneous disintegration of excited nuclei with the emission of radiation in the form of particles and/or electromagnetic waves. Let's now take a look at the sources of radioactive nuclei.

Some radioactive nuclides are found in nature. Significant among these are the heavy elements uranium and thorium which decay through a series of other radioactive nuclides to become stable isotopes of lead. It is believed relatively large numbers of these elements were present at the time the earth was formed. Over the life of the earth, their concentrations have been reduced by radioactive decay.

Another significant naturally occurring radionuclide is potassium-40. Potassium-40 is noteworthy since it is a normal constituent of the human body (an average 160 lb person contains about 0.031 grams of it).

Other radioactive nuclides, which are found in nature, are produced in the upper atmosphere by cosmic ray bombardment. Since this is a continuous process, the concentrations of these nuclides are relatively constant. Two nuclides, which are formed by cosmic ray bombardment, are tritium (hydrogen-3) and carbon-14. Tritium is significant since it behaves the same as ordinary hydrogen, so it may be found combined with oxygen to form water. Carbon-14 is used as a method of determining the age of prehistoric biological matter.

Man has created many other radioisotopes. Some are deliberately produced for medical, industrial and military purposes. Others are byproducts of power production from nuclear fission.

In this lesson, we will take a closer look at types of radioactive decay and the mechanisms involved. Considered will be the composition and characteristics of the radiation and the resulting changes in the radionuclides. Information on the rate of radioactive decay will also be presented.
OBJECTIVES

TERMINAL OBJECTIVE
The Contractor Health Physics Technician will describe the principles of radioactive decay including the radioactive decay equation, nuclear stability curve, and parent/daughter isotopic relationships.

ENABLING OBJECTIVES
Upon completion of this lesson, the Contractor Health Physics Technician will be able to:

1. Define half life.

2. Recognize the radioactive decay equation.

3. Describe the relationship between the radioactive decay constant and the half-life of an isotope.

4. Solve or manipulate radioactive decay problems given the use of a calculator, the quantity of curies of an isotope, and its half-life.

5. Describe the characteristics of beta, positron, and alpha decay processes.
1.0 RADIOACTIVE DECAY

Radioactive decay is a process a nucleus undergoes in the transition to a more stable state. When a decay process has occurred, the new nucleus, which is formed, is called the daughter nucleus. It may also be radioactive and hence decay.

Fission products are usually unstable due to their high neutron to proton ratio. They seek a stable configuration usually in a series of beta decays, which lowers their $\eta/\rho$ ratio. Isotopes produced by bombardment with sub-atomic particles are also unstable.

To better describe decay processes, standard notation is used in two forms, as shown in Figure NP-3-1.

The parent nucleus, denoted by X, is transformed into the daughter nucleus Y, accompanied by radiation $\gamma$. The first form of notation is an equation. It is always true that the number of neutrons and protons (A) and the total charge (Z) must be conserved. The second form is a description of the reaction. Once one becomes familiar with all decay processes, the second form of notation becomes standard.

The total mass/energy must also be conserved according to $E = mc^2$. The total mass of the products must be less than the mass of the parent nuclide. This decrease in mass is converted to energy, which manifests itself in the form of kinetic energy of the daughter product (Y), and the energy of the radiation ($\gamma$). The parent nucleus (X) is normally assumed to be at rest. If it is not, its kinetic energy must be included in the mass/energy balance.
1.1 ALPHA DECAY

An alpha particle (α) is essentially a helium nucleus (2 protons and 2 neutrons). It has a +2 charge and atomic mass of 4.

Heavy nuclei, i.e., those having a mass number greater than 210, are capable of decaying through the emission of an alpha particle. Consider what happens to the emitting nuclide (called the parent nuclide, designated X) when an alpha particle is ejected. The parent nuclide mass number is reduced by 4 and its atomic number is reduced by 2. The resultant nuclide is called the daughter nuclide, designated Y. The general formula for alpha decay is given in Figure NP-3-2.

The E designates energy given off in the reaction in the form of a gamma ray. Almost all alpha decay reactions are accompanied by the emission of a gamma ray.

A important characteristic of alphas is that a given radionuclide will emit alphas with certain definite energy levels. Many isotopes emit alphas of only one energy. For example, uranium-238 emits alpha of 5.2 Mev only, while uranium-235 emits alphas with 4.39 and 4.56 Mev energies.

1.2 BETA MINUS DECAY

A beta particle is an electron emitted from the nucleus of a radioactive isotope. According to modern theory, a neutron in the nucleus transforms into a proton and an electron, with the electron emitted as a high speed beta particle

$$\eta \rightarrow \rho^+ + e^-$$

This decreases the number of neutrons and increases the number of protons in the nucleus. Nuclides with too high a $\eta/\rho$ ratio undergo beta minus decay in order to bring the $\eta/\rho$ ratio closer to the stable region.
NP-3-3  Beta Decay

Unlike alpha emitters, beta emitters do not emit particles at discrete energies. Each beta emitter emits betas over a wide spectrum of energies with only the maximum beta energy being characteristic of the parent nuclide.

The change in energy states of the parent nuclide is always equal to the maximum beta energy. Thus, when a beta particle of less than maximum energy is emitted, the remaining energy must be released by another means. It has been found that there is another particle of negligible mass and zero charge which accompanies beta decay; it is called an anti-neutrino.

The anti-neutrino satisfies the laws of conservation for a beta decay reaction. The symbol for an anti-neutrino is \( \nu \). The energy, \( E \), resulting from the conversion of mass from the parent nuclide (X) to the daughter nucleus (Y) is distributed among the energies of the resultant products. On the average, the beta acquires about 40% of the energy. Thus, the general formula for beta-minus decay is shown in Figure NP-3-3.

Note that the conversion of a neutron to a proton causes the atomic number of the daughter nuclide (Y) to be one greater than that of the parent (X). Also note that the A number did not change.

The following are actual examples of beta-minus decay reactions:

\[
\begin{align*}
90 \text{Th}^{234} & \rightarrow 91 \text{Pa}^{234} + \beta^{-} + \nu \\
6 \text{C}^{14} & \rightarrow 7 \text{N}^{14} + \beta^{-} + \nu
\end{align*}
\]

1.3  GAMMA EMISSION

Gamma emission is a process whereby a nucleus releases its excess energy by emitting a gamma ray. Most daughter products from alpha and beta decay are left in an "excited state", in that they contain excess energy. Another common example is the absorption of a neutron by a nucleus, raising the nucleus to an excited state. This excess energy is released in the form of one or more gamma rays. Since gamma rays have no mass or charge, the nucleus remains unchanged except for the fact it is in a lower energy state. The equation for gamma emission is shown in Figure NP-3-4.
NP-3-4 Gamma Emissions

The asterisk (*) to the right of the parent nucleus denotes an excited state.

There are a number of discrete energy states to which a nucleus can be raised, similar in principle to the discrete states in which orbital electrons can be raised.

Hence, the excited nuclei have specific amounts of excess energy, which they must release in order to return to the "ground state". The excited nucleus then emits gamma ray(s) at discrete energy levels in order to reach the ground state, as shown in Figure NP-3-5.

\[
\begin{array}{c}
\text{EXCITED STATES} \\
\text{1} \quad \text{E1} \\
\text{2} \quad \text{E2} \\
\text{3} \quad \text{E4}
\end{array}
\]

\[
\begin{array}{c}
\text{GROUND STATES} \\
\text{E2} \\
\text{E3} \\
\text{E5}
\end{array}
\]

NP-3-5 Gamma Emission Energy States

1.4 ELECTRON CAPTURE/BETA PLUS DECAY

In instances where the n/p ratio is below the stability region, a nucleus can decay by electron capture or beta plus emission in order to increase the ratio of neutrons to protons. These processes are rare when compared to previously discussed decay modes.

In electron capture, a proton in the nucleus absorbs an orbital electron from the innermost shell (K shell) and becomes a neutron. To satisfy the laws of energy conservation, a neutrino particle is emitted. The reaction equation for electron capture is:

\[
zX^A + ^{-1}e^0 \rightarrow z^{-1}Y^A + 0\nu^0 + E
\]
Note that electron capture results in a new nucleus with Z decreased by one.

Electron capture always results in the emission of X-rays which are given off as higher energy state electrons "fall" into the vacancies created by the captured K shell electron.

Beta plus decay is the emission of a positron (positively charged electron) from the nucleus. The positron comes from a proton, which transforms into a positron and a neutron. The resultant nucleus again has a Z decreased by one and the same A number as before. Beta plus decay is also accompanied by a neutrino. The reaction equation for beta plus decay is:

\[ Z \ X^A \rightarrow Z - 1 \ Y^A + 0\nu + +1e^0 + E \]

1.5 NEUTRON EMISSION

In some cases, nuclei with too high a \( \eta / \rho \) ratio for stability possess enough excess energy to directly emit a neutron. The fission process, results in 2 highly excited "fission fragments" with a high \( \eta / \rho \) ratio. Some of these fission fragments possess the energy required to directly emit a neutron. This usually occurs immediately after the formation of the excited nucleus. The reaction equation for neutron emission is:

\[ Z \ X^A \rightarrow Z \ X^{A-1} + 0n + E \]

1.6 SPONTANEOUS FISSION

Transuranic elements - elements with a Z number \( \geq 92 \), can undergo spontaneous fission. This process is rare, these elements normally undergo alpha decay. If one of these elements gets enough excitation energy it may split into two daughter products releasing gammas and neutrons and a large amount of energy. Some examples of elements, which undergo spontaneous fission, are U-235, U-238 and Pu-239. The fission process will be discussed in detail in a later lesson.

2.0 ARTIFICIALLY PRODUCES RADIOACTIVE MATERIALS

If stable (non-radioactive) nuclei are bombarded with alpha, beta, neutron, etc., the particles are frequently captured in the nuclei and new isotopes (and elements) result.
Most of the isotopes formed in this manner have excess energy and thus are radioactive. This is a frequent phenomena in nuclear reactor cores where structural materials are subject to high levels of radiation.

3.0 DECAY RATES AND HALF LIVES

The process of radioactive decay is largely a statistical one. It is not possible to point to a particular nucleus and determine when it will decay. However, for large amounts of a given radionuclide, statistics may be applied to determine how long it takes for a given portion of the sample to undergo decay. The unit used to describe the probability of radionuclide decay is half-life (t). Half-life is defined as the time it takes for one half of a sample of radioactive material to decay to something else. For example; if we had a sample of radioactive material containing 100,000 atoms with a half-life of 1 hour, after 1 hour 50,000 would have decayed. After 2 hours, or 2 half lives, only 25,000 of the original atoms remain, etc... Remember, the material is not disappearing, it is decaying to another substance. A graphical representation of radioactive decay is shown in Figure NP-3-6 both on a linear and semi-logarithmic graph.

![Radioactive Decay Plots](NP-3-6)

It should be clear from Figure NP-3-6 that radioactive decay is an exponential function. The exponential decay of a radionuclide over time may be expressed as:

\[ N = N_0 e^{-\lambda t} \]

Where: \[ N = \text{amount of radionuclide at any time (t)} \]
No = the original amount of radionuclide

e = base of the natural log (2.718...)

\( \lambda \) = decay constant for the radionuclide

t = time

This equation has introduced a new term \( \lambda \) (lambda). \( \lambda \) is the decay constant, it is closely related to half-life. To convert from half-life to decay constant (or vice versa) the following relationship is used:

\[
\lambda = \frac{\ln 2}{t/\tau} = \frac{0.693}{t/\tau}
\]

NOTE: The decay constant (\( \lambda \)) and the half-life are constants for a given radionuclide. These values do not change with time, temperature, chemical state or physical state of the material. Given the decay constant or half-life, one can determine how much of a particular radionuclide is present at any time during its decay process.

Example: A radioactive source contains \( 4 \times 10^{19} \) atoms of cobalt-60 with a half-life of 5.3 years. How many atoms of cobalt-60 will remain after 2 years?

\[
N = N_0 e^{-\lambda t}
\]

\[
\lambda = \frac{0.693}{\tau/\tau} = 0.1307 \frac{1}{\text{yrs}}
\]

\[
N = \left(4 \times 10^{19}\right) e^{-0.1307 \left(\frac{1}{\text{yrs}}\right) \times 2 \text{yrs}}
\]

\[
N = 3.08 \times 10^{19} \text{ atoms}
\]

3.1 THE CURIE

We are often more interested in the rate of radiation emission from a radioactive material than how much remains after a certain period of time. The unit used to express the rate at which a radioactive sample decays is the curie. The curie is a unit of activity. The curie was named after Marie and Pierre Curie who discovered that one gram of radium decayed at a rate of \( 3.7 \times 10^4 \) disintegrations per sec (dps). This amount of activity was designated as one curie.
The activity of a given sample of radioactive material can be found by multiplying the decay constant \( \lambda \) times the number of radionuclides present \( N \).

\[ A = \lambda N \]

Knowing that \( N \) decreases exponentially with time, it follows that activity will do the same.

Since,

\[ A = \lambda N \]

And,

\[ N = N_0 e^{-\lambda t} \]

Then,

\[ A = \lambda N_0 e^{-\lambda t} \]

And,

\[ A_0 = \lambda N_0 \] (right?)

Then,

\[ A = A_0 e^{-\lambda t} \]

Activity follows the same exponential decay law as \( N \).

Example:

How many curies of activity are there in a sample of radioactive xenon-135 which contains \( 10^{18} \) atoms?

How many curies will remain after 1 day?

Xenon-135 decays by beta-minus decay with a half-life of 9.1 hours.

\[ \lambda = \frac{0.693}{t_{1/2}} \]

\[ \lambda = \frac{0.693}{9.1 \text{hrs}} = 0.076/\text{hr} \]

\[ A = \left(0.076/\text{hr}\right)(10^{18} \text{ atoms}) = 7.6 \times 10^{16} \frac{\text{disintegrations}}{\text{hr}} \]

\[ 7.6 \times 10^{16} \frac{\text{disintegrations}}{\text{hr}} \left(\frac{1 \text{ hr}}{60 \text{ min}}\right) \left(\frac{1 \text{ min}}{60 \text{ sec}}\right) = 2.1 \times 10^{13} \text{ dps} \]

\[ 2.1 \times 10^{13} \text{ dps} \left(\frac{1 \text{ curie}}{3.7 \times 10^{10} \text{ dps}}\right) = 567 \text{ curies} \]
After 1 day: $A = A_0 e^{-\lambda t}$

$A = 567 \text{ curies } e^{-\left(0.076/\text{hr}\right)(1 \text{ day})(24 \text{ hrs/day})}$

$A = 91 \text{ curies after 1 day}$

4.0 SUMMARY

The manner in which a radioactive nuclide decays depends upon a number of factors. One major factor is the neutron to proton ratio. If the $\eta / \rho$ ratio is too high, the nucleus will most likely beta-minus decay. If it is too low, it may decay by beta plus decay or electron capture. Heavy nuclides often decay by alpha emission. At this point, the student should be able to discuss the decay modes and write the general notation for each process.

The rate at which a sample of radioactive material decays and the energy of the radiation emitted, help identify the isotopes contained in the sample. Also, these factors dictate the hazard to personnel who may be nearby or even in contact with the radioactive material. The student should be able to solve problems concerning rates of decay and curie content.