Course Title: **Radiological Control Technician**
Module Title: **Radioactivity & Radioactive Decay**
Module Number: **1.06**

Objectives:

1.06.01 Identify how the neutron to proton ratio is related to nuclear stability.

1.06.02 Define the following terms:

a. Radioactivity
b. Radioactive decay.

1.06.03 Identify the characteristics of alpha, beta, and gamma radiations.

1.06.04 Given simple equations, identify the following radioactive decay modes:

a. Alpha decay
b. Beta decay
c. Positron decay
d. Electron capture.

1.06.05 Identify two unique aspects associated with the decay of a radioactive nuclide.

1.06.06 Identify differences between natural and artificial radioactivity.

1.06.07 Identify why fission products are unstable.

1.06.08 Identify the three naturally occurring radioactive families and end-product of each.

1.06.09 Given a nuclide, locate its block on the Chart of the Nuclides and identify the following for that nuclide:

a. Atomic number
b. Atomic mass
c. Natural percent abundance
d. Stability
e. Half-life
f. Types and energies of radioactive emissions.

1.06.10 Given the Chart of Nuclides, trace the decay of a radioactive nuclide and identify the stable end-product.

1.06.11 Define the following units:

a. Curie
b. Becquerel.

1.06.12 Define specific activity.

1.06.13 Define half-life.

1.06.14 Calculate activity, time of decay, and radiological half-life, using the formula for radioactive decay.

1.06.15 Define the following:

a. Exposure
b. Absorbed dose
c. Equivalent dose
d. Radiation weighting factor.

1.06.16 Define the following units:

a. Roentgen
b. Rad/gray
c. Rem/sievert.

INTRODUCTION

As discussed in previous lessons, there are many different kinds of elements. The atoms of these elements are composed of a nucleus surrounded by orbital electrons. The nucleus consists of protons and neutrons. Each element has a specific number of protons, while the number of neutrons may vary, resulting in various isotopes of the same element.

In addition, a slight difference in mass-energy exists between a composite nucleus and the sum of the free-standing nucleons; that difference being the energy that binds the nucleus together. This indicates that each nucleon, i.e., proton or neutron, give up a certain amount of its mass-energy in order for the nucleus to hold together. Because only isotopes exist in nature, this must mean that only specific combinations of neutrons and protons are possible for the existence of the unchanging stable nuclei. Variations from these specific combinations are possible, but the nuclei may not be completely stable. In other words, there may be more energy present in the nuclei of some isotopes than is required to hold them together. With that excess of energy nuclei will not be stable and will, most likely, dissipate it in some manner, in order to become stable.

Stable nuclei will remain unchanged as long as there is no external influence causing them to become unstable. Unstable nuclei, however, will spontaneously emit excess energy and transform into more stable nuclei. Such transformations are independent of external influences such as temperature or chemical reactions of the atom. The emission of excess energy by unstable nuclei in order to achieve stability is the phenomenon of radioactivity.

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1.06.01 Identify how the neutron to proton ratio is related to nuclear stability.

NUCLEAR STABILITY

Forces in the Nucleus

Nuclear stability is governed by the particular combination and arrangement of neutrons to protons in a given nucleus. The stability of the nucleus is affected by three forces acting in the nucleus (see Table 1):

Table 1. Forces Acting in the Nucleus

Force	Interaction	Range
Gravitational	Negligible *attractive* force between all nucleons	Relatively long
Electrostatic	Strong *repulsive* force between like charged particles (protons)	Relatively long
Nuclear Force	Strong *attractive* force between all nucleons	Extremely short

The gravitational and electrostatic forces can be calculated using principles from classical physics. In doing so, it is found that the gravitational force is so small that it can be neglected. The repulsive electrostatic force between protons is found to be quite significant and occurs much farther than the dimensions of a nucleus. If only these two forces existed in the nucleus, then it would be impossible to have stable nuclei with more than one proton. The gravitational forces are much too small to hold the nucleons together compared to the electrostatic forces repelling the protons. Because stable atoms do exist, there must be another, attractive, force acting within the nucleus.

The nuclear force is independent of charge. It acts equally only between pairs of neutrons, pairs of protons, or a neutron and a proton. Because the range of the nuclear force is much shorter than the range of the electrical force, neutrons can only interact with those nucleons to which they are immediately adjacent, whereas protons interact with each other even though remotely located within the nucleus. Since the repulsive forces associated with protons will be significant regardless of their location in the nucleus, the repulsive forces will have a large impact on the nuclear stability. For this reason, the number of neutrons in the nuclei of heavier isotopes must increase more rapidly than the number of protons in order to maintain stability.

Neutron/Proton Ratio

In a stable atom, there is a balance between the attractive (nuclear) and repulsive (electrostatic) forces in the nucleus. If the forces do not balance out, the atom cannot be stable. This means that only certain combinations or ratios of neutrons and protons are stable such that the repulsive force is balanced by the attractive forces. The coulomb (electrostatic) forces become increasingly

significant as the atomic number – the number of protons, increases above 20. Consequently, with increasing atomic number an excess of neutrons over protons is required for a stable nuclide.

Thus, for elements in the Periodic Table with low atomic numbers, greater nuclear stability is found when the number of neutrons is about equal to the number of protons. As elements increase in Z number (number of protons) above 20, the neutron to proton ratio (n:p ratio) gradually increases until Z=83 (bismuth), where the n:p ratio required for stability exceeds 1.5 to 1. Finally, at the high atomic number part of the Periodic Table, above $^{209}_{83}$Bi , there are no completely stable nuclei (just recently it was found that $^{209}_{83}$Bi is radioactive with the half life of ~$2x10^{19}$ yr - that makes it a practically stable isotope)

The stable range can be graphed and is usually called the *line of stability*. The graph shows a dashed line representing a 1:1 ratio of neutrons to protons for any Z number (see Figure 1). The actual "line" of stability is represented by the ratio of neutrons to protons for naturally occurring stable isotopes. The line of stability graph can be thought of as a simplified representation of the Chart of the Nuclides. The number of neutrons (N) is the "x-axis" and number of protons (Z) is the "y-axis."

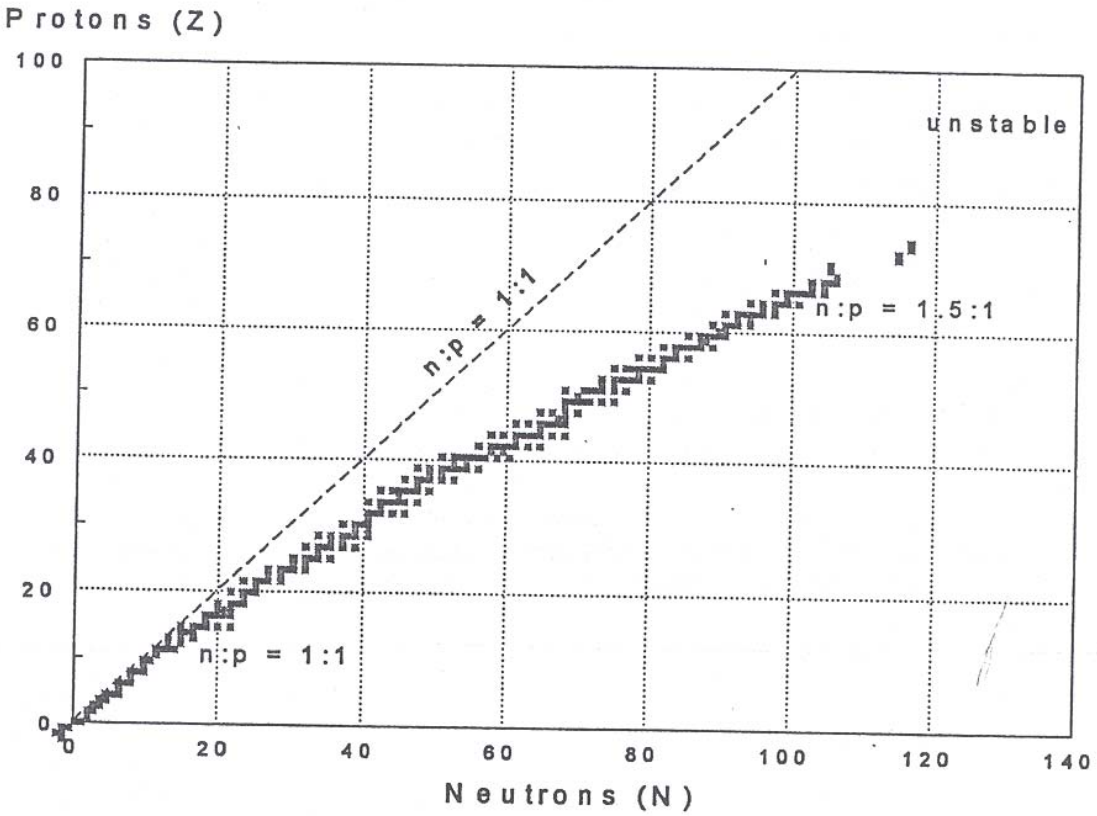


Figure 1. Neutron:Proton Ratios for Stable Nuclides

The stability conditions based on n:p ratios are not very critical, and a stable range of n:p ratios exists for many elements. For a given atomic number, conditions may vary widely, such that numerous stable isotopes (same atomic number, different mass numbers) can occur for a particular element as many as 10 stable isotopes for some elements. For a given mass number, there may be several stable arrangements of protons and neutrons resulting in several stable isobars (same mass number, different atomic numbers).

Stability Ranges

In summary, nuclear stability is governed by the particular combination and arrangement of neutrons and protons in a given nucleus. If the combination and arrangement of neutrons and protons does not fall within a stable "range," the nucleus is unstable. An unstable nucleus attempts to achieve stability by changing its nuclear configuration. This will be accomplished by transformations of surplus nucleons (protons and neutrons) in order to balance the forces within the nucleus. When a proton or neutron in the nucleus is transformed (to be discussed later), the ratio of neutrons and protons is thereby changed.

1.06.02 Define the following terms:

a. Radioactivity
b. Radioactive decay.

RADIOACTIVITY

Radioactivity is manifested by a spontaneous emission of energy from a nucleus, that is, emission of radiation, in the forms of particles and packets of electromagnetic waves (photons). The emission of particles follows the process of transformation of a neutron into a proton or of a proton into neutron. In either case the configuration of a nucleus is altered toward more stable p:n ratio. Very often such transformations are followed by emission of more energy in the form of photons – gamma rays. However, when all excess energy within a nucleus is radiated out (zero energy level), an equilibrium of forces within the nucleus, is attained, and it becomes stable.

In the process of a proton or neutron transformations, a nucleus emits, or even captures a charged particle (an electron from the K or L shell), thus a *transmutation* of a nuclide occurs; it literally, becomes atom of another chemical element.

The nuclei of a radioactive isotope (nuclide) shed their excess energy – radiate, rather spontaneously, but also, randomly, over a certain period of time. Thus even we know that a nuclide is radioactive, we do not know when a particular nucleus will radiate its excess energy and become more stable. However, we know that after a certain length of time a half of the present number of nuclei will be transformed. That time is called the half life of a nuclide, $\mathbf{t_{1/2}}$.

Following a transformation the nucleus is more stable than it was, but it may not be completely stable. So, another transformation will take place in which the nucleus will again emit radiation. The amount of energy given off and the type of emission that occurs will depend on the

configuration of the nucleus immediately before a specific transformation occurs. Each step in the series of transformations will mean a distinct reduction in total mass-energy of the nucleus. As the energy of the nucleus is reduced, the nucleus is said to ***disintegrate*** or decay. The **process by which a nucleus spontaneously disintegrates; (or is transformed) through one or more discrete energy steps until a stable state is reached,** is called ***radioactive decay***.

The nucleus before the decay (or transformation) is called the *parent*, and the nucleus after the decay is called the *daughter*. When there is a series of transformations before a stable state is reached, the daughter of one decay event may, also, be radioactive and thus be the parent to another daughter. As the various steps from parent to daughter are traced to stability, a series of transmutations is seen, called a *decay chain*. The complete chain includes the original parent, all of its daughters and the final, stable end-product. Examples of various decay chains will be shown throughout the remainder of this lesson.

Nature of Radioactivity

Certain nuclides are unstable as they occur in nature and are, therefore, referred to as being *naturally* radioactive. Others are *artificially* radioactive because they have become radioactive as a result of some man-made reaction. Evidence of natural radioactivity was first reported by Henri Becquerel in 1896. Becquerel demonstrated that uranium ore would darken a photographic plate shielded with opaque paper in much the same manner as X-rays. He postulated that the uranium emitted very penetrating rays, similar to X-rays. The phenomenon ultimately was called radioactivity (by Marie Curie). In time, it was determined that there were many elements beyond the atomic number of lead (Z=82) which showed similar radiating characteristics.

After a long and complicated series of investigations, to which many outstanding physicists contributed, a better understanding of natural radioactivity was available. That understanding culminated with the experiments of Ernest Rutherford. In 1903, he definitely (magnetically) separated three kinds of radioactive emissions, which he named alpha, beta, and gamma, after the first three letters of the Greek alphabet.

1.06.03 Identify the characteristics of alpha, beta, and gamma radiation.

MODES OF DECAY AND TYPES OF RADIOACTIVE EMISSIONS

As mentioned above, Rutherford was able to separate and name three types of radiation resulting from radioactive decay: alpha, beta, and gamma. Initially, all three radiations were commonly referred to as the rays. Rutherford clearly determined and confirmed the characteristics of each of these radiations. It was found that alpha and beta are actually *particulate* radiations, not rays. Since then, other radiations have been discovered through numerous experiments and tests.

1.06.04 Given simple equations, identify the following radioactive decay modes:

- ***a. Alpha decay***
- ***b. Beta decay***
- ***c. Positron decay***
- ***d. Electron capture***

Alpha Decay

With a few exceptions, only relatively heavy radioactive nuclides decay by alpha emission. An alpha particle is essentially a helium nucleus. It consists of two protons and two neutrons, giving it a mass of 4 amu. Because of the two protons it has an electric charge of +2. The symbol α is used to designate alpha particles.

A nucleus emitting an alpha particle decays to a daughter element, reduced in atomic number by 2 and reduced in mass number *(A)* by 4. The standard notation for alpha decay is:

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

For example, Radium-226 decays by **alpha emission** to produce Radon-222 as follows:

$$ {}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha $$

Alpha particles are the least penetrating of the three types of radiation. They can be absorbed or stopped by a few centimeters of air or a sheet of paper.

Beta Decay

A nuclide that has an excess number of neutrons (i.e., the n:p ratio is high) will usually decay by changing a neutron into a proton through an emission of a negatively charged particle – beta particle. Beta particles have the same mass as an electron (1/1836 of proton or 5.49E-4 amu) as well as the same charge (-1), and can be considered high speed electrons. Because of the negative charge of the beta particle, beta emission is often more explicitly referred to as "beta-minus" emission (the particle sometimes being referred to as a *negatron*). Beta particles originate in the nucleus, in contrast with ordinary electrons, which exist in orbits around the nucleus. The symbol β^- is used to designate beta particles.

In beta-minus emitters, the nucleus of the parent gives off a negatively charged particle, resulting in a daughter more positive by one unit of charge. Because a neutron has been replaced by a proton, the atomic number increases by one, but the mass number is unchanged. There is also the emission of an antineutrino, symbolized by the Greek letter nu with a bar above it ($\bar{\nu}$).

The standard notation for beta decay is:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^{-} + \bar{\nu} $$

For example, Lead-210 decays by **beta-minus emission** to produce Bismuth-210 as follows:'

$$ {}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi + \beta^{-} + \bar{\nu} $$

Beta particles are emitted with kinetic energies ranging up to the maximum value of the decay energy, $E_{max.}$ The average energy of beta particles is about 1/3 E_{max}. They travel several hundred times the distance of alpha particles in air and require a few millimeters of aluminum to stop them.

Neutrinos (ν) and *anti-neutrinos* ($\bar{\nu}$) are neutral (uncharged) particles with negligible rest mass, travel at the speed of light, and almost never interact with matter. They account for the energy distribution among positrons and beta particles from given radioactive nuclides in the positron and beta-decay processes, respectively.

Positron Decay

A nuclide that has a low n:p ratio (too many protons) will tend to decay by positron emission. A positron is often mistakenly thought of as a positive electron. If positive electrons existed, then when they encountered an ordinary negative electron, the coulomb (electrostatic) force would cause the two particles to accelerate toward each other. They would collide and then the two equal but opposite charges would mutually cancel. This would leave two neutral electrons. Actually, a positron is the anti particle of an electron (e^-). This means that along with the opposite charge, i.e., (+1), of an electron or beta particle (β^-), other intrinsic characteristics of a positron are opposite to the characteristics of an electron. Thus, the positron is a positively charged, high-speed particle that originates in the nucleus. Because of its positive charge and a rest mass equal to that of a beta particle, a positron is sometimes referred to as “beta plus.” The symbol β^+ is used to designate positrons.

With positron emitters, the parent nucleus changes a proton into a neutron and gives off a positively charged particle. This results in a daughter less positive by one unit of charge. Because a proton has been replaced by a neutron, the atomic number decreases by one, and the mass number remains unchanged. The emission of a *neutrino* (symbolized by ν) also occurs in conjunction with the positron emission.

Positron decay is illustrated by the following notation:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^{+} + \nu $$

For example, Nickel-57 decays by positron emission:

$$^{57}_{28}Ni \rightarrow ^{57}_{27}Co + \beta^{+} + \nu$$

Electron Capture

For radio nuclides having a low n:p ratio, another mode of decay can occur known as orbital *electron capture* (EC). In this radioactive decay process, the nucleus captures an electron from an orbital shell of the atom, usually the K shell, because the electrons in that shell are closest to the nucleus. The nucleus might conceivably capture an L-shell electron, but K-electron capture is much more probable. This mode of decay is frequently referred to as *K-capture*. The transmutation resembles that of positron emission, as follows:

$$^{A}_{Z}X + e^{-} \rightarrow ^{A}_{Z-1}Y + \nu$$

The electron combines with a proton to form a neutron, followed by the emission of a neutrino. Electrons from higher energy levels immediately move in to fill the vacancies left in the inner, lower-energy shells. The excess energy emitted in these moves results in a cascade of *characteristic X-ray* photons.

Either positron emission or electron capture can be expected in nuclides with a low n:p ratio. The intra-nuclear effect of either mode of decay would be to change a proton into a neutron, thus increasing the n:p ratio.

Note that ^{57}Ni has two modes of decay. This is an example of branching that is explained in the section **DECAY PHENOMENA**.

$$^{57}_{28}Ni + e^{-} \rightarrow ^{57}_{27}Co + \nu$$

Gamma Emission

Gamma emission is another type of radioactive decay. Nuclear decay reactions resulting in a transmutation generally leave the resultant nucleus in an excited state. Nuclei, thus excited, may reach an unexcited or *ground state* by emission of a gamma ray.

Gamma rays are a type of electromagnetic radiation. They behave as small bundles or packets of energy, called *photons*, and travel at the speed of light. In general, gamma radiation is the same as X-rays. Gamma rays are usually of higher energy (MeV), whereas X-rays are usually in the keV range. The basic difference between gamma rays and X-rays is their origin; gamma rays are emitted from the nucleus of unstable atoms, while X-rays originate in the electron shells. The basic difference between gamma rays and visible light is their frequency. Gamma rays and X-

rays are of a much higher frequency than visible light. The symbol γ is used to designate gamma radiation.

Because the gamma decay doesn't involve the gain or loss of protons or neutrons, the general equation is slightly different from the other decay equations.

$$ {}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma $$

All the transmutation examples given could be accompanied by gamma emission. Although most nuclear decay reactions do have gamma emissions associated with them, there are some radionuclide species that decay by particulate emission with no gamma emission.

Table 2 provides a summary of the characteristics of the various types of radioactive emissions that have been discussed. Table 3 summarizes the various modes of radioactive decay.

Table 2. Types of Radioactive Emissions

Radiation	Symbol	Form	Origin	Essential Parts	Mass (amu)	Charge	Energy Spectrum	Miscellaneous information
Alpha	α	Charged particle	nucleus	2p,2n	4	+2	MeV	mono-energetic; from heavy radionuclides
Beta[-minus] (Negatron)	β^-	Charged particle	nucleus	$1e^-$	«1	-1	0 to max	fission products
Gamma	γ	Electromagnetic Radiation	nucleus	photon	none	none	MeV	usually follows particle emission
X-ray	X	Electromagnetic Radiation	electron orbitals	photon	none	none	keV	cascade following EC; Bremsstrahlung
Positron (Beta plus)	β^+	Charged particle	nucleus	antimatter equivalent of $1e^-$	«1	+1	0 to max.	will annihilate with e^-
Neutron	n	Uncharged particle	nucleus	1n	1	0	eV to MeV	born “fast”
Proton	p	Charged particle	nucleus	1p	1	+1	keV to MeV	scattered in neutron interactions
Ion/Fission fragment	FF	Charged particle	nucleus	light and heavy nuclei	varies	»1	MeV	result front fission
Neutrino	ν	Uncharged particle	nucleus	—	.0	0	MeV	from β^+decay
Antineutrino	$\bar{\nu}$	Uncharged particle	nucleus	—	.0	0	MeV	from β^-decay

Table 3. Modes of Decay

Decay Mode	Equation	Nuclear Transformation	Example
Alpha	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$	$2p + 2n \rightarrow \alpha$	${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}\alpha$
Beta	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^{-} + \bar{\nu}$	$n \rightarrow p^{+} + e^{-} \rightarrow \beta^{-}$	${}^{32}_{15}P \rightarrow {}^{32}_{16}S + \beta^{-}$
Positron	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^{+} \nu$	$p \rightarrow n + \beta^{+} \rightarrow \beta^{+}$	${}^{123}_{56}Ba \rightarrow {}^{123}_{55}Cs + \beta^{+}$
Electron Capture (EC) or K-capture	${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu$	$p + e^{-} \rightarrow n$	${}^{136}_{62}Sm + e^{-} \rightarrow {}^{136}_{61}Pm$
Gamma	${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$	$E \rightarrow \gamma$	${}^{198}_{79}Au^{*} \rightarrow {}^{198}_{79}Au + \gamma$

Other Types of Transformations

Internal conversion

This phenomenon occurs when a gamma photon does not escape the electron cloud surrounding the nucleus but transfers to one of the orbital electrons all of its energy and, eventually, eject it from the atom. The photon is 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. This process usually takes place in the K-shell. There will then follow emission of characteristic X-rays as with electron capture. In principle, it is similar to the photoelectric effect (to be discussed in Lesson 1.07).

Isomeric transition

Isomeric transition commonly occurs immediately after particle emission. However, the resulting nucleus may remain in an excited state for a measurable period of time before dropping to the ground state at its own characteristic rate of decay i.e., half life. A nucleus that remains in such an excited state is known as an *isomer* because it is in a *metastable* state; that is, it differs in energy from other nuclei with the same atomic number and mass number. Generally, the isomer achieves ground state by emitting delayed gamma radiation, i.e. according to its own rate of decay – half life.

The metastable or excited state, is usually represented by a small m following the mass number, A, in the standard nuclide notation. For example, Technetium-99m and Technetium-99 are isomers. $^{99m}_{43}\mathrm{Tc}$ will decay to $^{99}_{43}\mathrm{Tc}$ with the emission of a 140.5 keV gamma. Further radioactive decay of the $^{99}\mathrm{Tc}$ may still occur for it decays at a very slow rate to $^{99}\mathrm{Ru}$, which is stable (see The Chart of Nuclides).

1.06.05 Identify two unique aspects associated with the decay of a radioactive nuclide.

DECAY PHENOMENA

Each radionuclide, artificial and natural, has its own characteristic pattern of decay. There are several aspects associated with this pattern:

- Modes of decay
- Types of emissions
- Energies of the emissions involved
- Rate of decay.

All nuclei of a given radionuclide attaining stability by radioactive decay do so in a specific manner. As indicated previously, ^{226}Ra decays by alpha emission, which is accompanied by a gamma photon. This represents the ***only*** mode of decay open to ^{226}Ra.

There are some radioactive nuclides that may have a choice of decay modes, i.e. there are nuclides exhibiting *branching* of decay modes. In such a case, a definite branching ratio exists. A case in point is the decay of ^{57}Ni, mentioned previously. This isotope of nickel decays 50% by K-capture and 50% by β^+emission. The branching ratio would be:

$$\frac{\beta^+}{EC} = 1$$

Not only do various radio nuclides disintegrate in a constant manner insofar as the *types* of emissions are concerned, but the emissions from each nuclide exhibit a ***distinct energy*** picture. The energies associated with radiations are given in terms of "million electron volts" (MeV). Beta emissions may occur with energies to about 5 MeV, alphas to about 10 MeV, and gamma photons to about 3 MeV. The energy of the particulate radiations is manifested as kinetic energy—the higher the energy the greater the velocity of the particle. However, the velocity of photons is constant (c = speed of lights) and energy differences are manifested by varying wavelengths i.e. frequencies.

The other characteristic aspect associated with decay patterns is the rate of decay or activity, i.e., the rate of disintegrations of radio nuclides being particular for each species. Such disintegrations are spontaneous and random. A single radium nucleus, for instance, may disintegrate at once or wait thousands of years before emitting an alpha particle. All that can be predicted with any certainty is that half of all the ^{226}Ra nuclei present will disintegrate in 1,622 years. This period is called the half-life of ^{226}Ra. Half-lives vary greatly for naturally occurring radioisotopes; e.g., ^{212}Po, with a half-life of 0.298 microseconds and ^{232}Th, with a half-life of over 1.42E10 years.

Singly - Occurring Natural Radio Nuclides

Careful measurements show that almost all materials contain traces of radioactivity. One might suspect that these traces might be due to some of the heavy radio nuclides belonging to one of the radioactive series described. However, some of the lighter elements are themselves radioactive.

Table 4. Naturally-occurring Radionuclides

Radionuclide	Half-Life	Alpha*	Beta*	Gamma*
$^{40}_{19}K$	1.26E9 yr	—	1.314	1.460
$^{87}_{37}Rb$	5.0 E 10 yr.	—	0.274	—
$^{147}_{62}Sm$	1.05E 11 yr.	2.23	—	—
$^{176}_{71}Lu$	3.0 E10 yr.	—	0.43	0.88 0.202 0.306
$^{187}_{75}Re$	4.0 E10 yr.	—	0.003	0.134

* Emission energies in MeV

Carbon-14 was not included as a natural radionuclide in Table 4, even though it has received considerable popular attention in recent years, because naturally occurring radiocarbon has been found in definite, though small, proportions. The ^{14}C existing in the atmosphere is being formed continually as a result of nuclear reactions between atmospheric nitrogen and neutrons from cosmic rays. This is shown in the following reaction:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

1.06.06 Identify differences between natural and artificial radioactivity.

Artificial Radioactivity

As discussed earlier, there are radio nuclides that occur as a result of various man-made nuclear reactions. These are called artificial radio nuclides. The vast majority of radio nuclides are produced in this manner.

As implied in the nomenclature, natural and artificial radioactive nuclides differ in origin. There are other distinctions between the two types that will be discussed. Nevertheless, the nuclei of artificial radio nuclides are unstable in much the same manner as their natural counterparts because the intra-nuclear factors governing decay are the same for both groups. A brief account of the discovery of artificial radioactivity will be given before further discussing its similarities and dissimilarities to natural radioactivity.

Induced Transmutations

In 1919, Lord Rutherford demonstrated that it was possible to produce artificially a *transmutation* of elements. The manner in which naturally-occurring radioactive atoms are changed or transmuted by emitting radiation has been discussed. Lord Rutherford set up and observed a nuclear reaction in reverse, whereby high-speed charged particles (projectiles) bombarded stable atomic nuclei (target), resulting in a reaction at the nuclear level and *inducing a transmutation.* The first observed nuclear reaction used alpha particles from ^{241}Bi (Radium C) as the charged particles. These were made to impinge on nitrogen nuclei, acting as the target. The reaction is written as follows:

$$^{14}_{7}N + ^{4}_{2}\alpha \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

Since the discovery of the transmutation of nitrogen, many hundreds of artificial or induced transmutations have been found. Until 1932, most induced transmutations were performed using naturally occurring alpha emitters as sources of incident particles. With the development of particle accelerators, many other bombarding particles have been successfully used.

Induced Radioactivity

During the first 15 years of experimental work with nuclear reactions, the transmutation products (insofar as could be observed) were NOT radioactive. However, the reactions generally were accompanied by the emission of a charged particle and a gamma ray. These emissions are not construed as imparting the property of radioactivity to the target element, because they occur practically instantaneously.

It was determined in 1934 that induced transmutations could produce nuclei that were residually unstable in somewhat the same manner as naturally occurring radio nuclides. Irene Curie and Frederic Joliot reported that certain light elements (boron, magnesium, aluminum), when bombarded with alpha particles, continued to emit radiation for a finite time after bombardment had stopped. The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of induced or artificial radioactivity:

$$^{27}_{13}Al + ^{4}_{2}\alpha \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

The resultant nucleus $^{30}_{15}\mathrm{P}$ was observed to be radioactive, emitting a small charged particle and reaching stability within minutes. The work of Curie and Joliot stimulated similar experiments throughout the world. As a result, radioactive isotopes of nearly every element in the Periodic Table were produced by bombarding a stable isotope with charged particles, neutrons, or in certain instances photons. Over 1,000 unstable nuclear species are listed in the Chart of the Nuclides.

Natural vs. Artificial

Heavy radio nuclides (natural and artificial) generally decay by a long series of alpha and beta emissions. Lighter, artificial radio nuclides, such as activation and fission products, usually decay by beta or positron emission or by orbital electron capture. In contrast to natural radioactivity, lighter artificially produced radio nuclides generally revert to stability in only a few decay steps.

1.06.07 Identify why fission products are unstable.

Fission Products

Another source of radio nuclides is nuclear fission. The nuclear fragments directly resulting from fission invariably have too large a proportion of neutrons to protons for stability, and consequently tend to achieve stability by beta minus emission. For example, consider fission of ^{235}U induced by thermal neutron reactions:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{55}Cs + ^{92}_{37}Rb + 2\left(^{1}_{0}n\right)$$

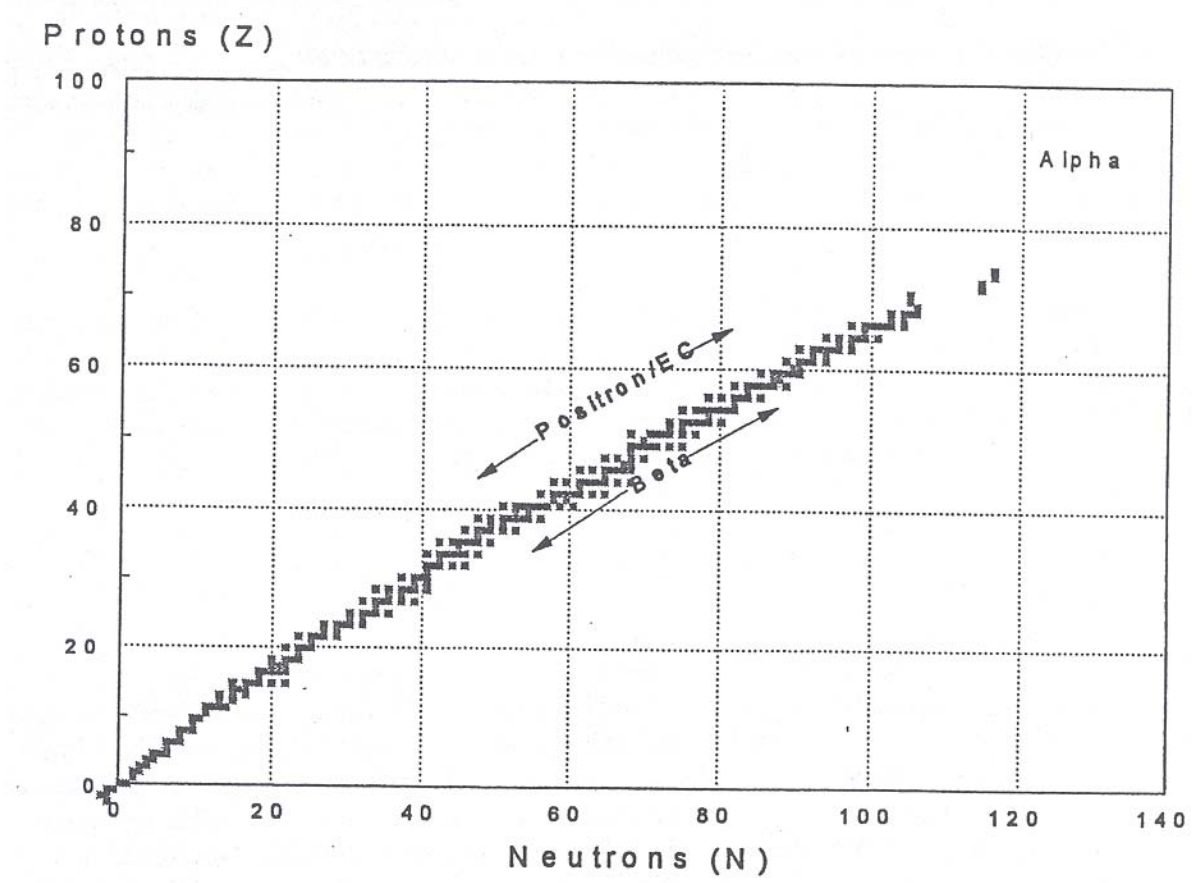
The n:p ratio for stable cesium (^{133}Cs) is 1.4:1, whereas the above fission product has a ratio of about 1.6:1. The stable ratio for rubidium (^{85}Rb) is 1.3:1, while the product above has a ratio of about 1.5:1. As can be seen, the fission products in the above equation have too many neutrons. Each fission fragment initiates a radioactive series, called a *fission decay chain,* involving several successive beta decay transformations. Fission product beta emission, as with other beta emitters, generally is accompanied by gamma emission.

Predicting Mode of Decay

Radioactive nuclides tend to decay in a way generating a daughter nuclide that lies closer to the line of stability. Generally speaking, nuclides below the line of stability will usually undergo beta-minus decay. Nuclides above the line of stability will usually undergo positron decay or electron capture. Nuclides at the upper end of the line of stability will usually undergo alpha decay. These are general rules that have many exceptions, especially in the region of heavy

nuclides. Figure 2 illustrates the type of decay nuclides in different regions will typically undergo.

Figure 2. Types of Decay Relative to Line of Stability



1.06.08 Identify the three naturally occurring radioactive families and the end-product of each.

RADIOACTIVE FAMILIES

The transmutations associated with naturally occurring radio nuclides frequently yield a daughter that is also radioactive. To date, about 70 different naturally occurring radio nuclides have been identified, each with its own characteristic pattern of radioactivity. Most of these yield radioactive daughters and are now known to be intimately interrelated in radioactive series or *families*.

Three Natural Decay Series

It has been established that radioactive species with Z > 82 belong to one of three independent groups or families (see Figure 3). Each family starts with a parent radionuclide, decaying or transmuting into a radioactive daughter nuclide, which would again transmute into a daughter nuclide, also radioactive, and so on until stability is attained. One family starts with uranium-238 ($^{238}_{92}$U) and is called the **uranium series**. Another starts with thorium-232 ($^{232}_{90}$Th) and is called the **thorium series**. A third starts with uranium-235 ($^{235}_{92}$U) and is called the **actinium series**.

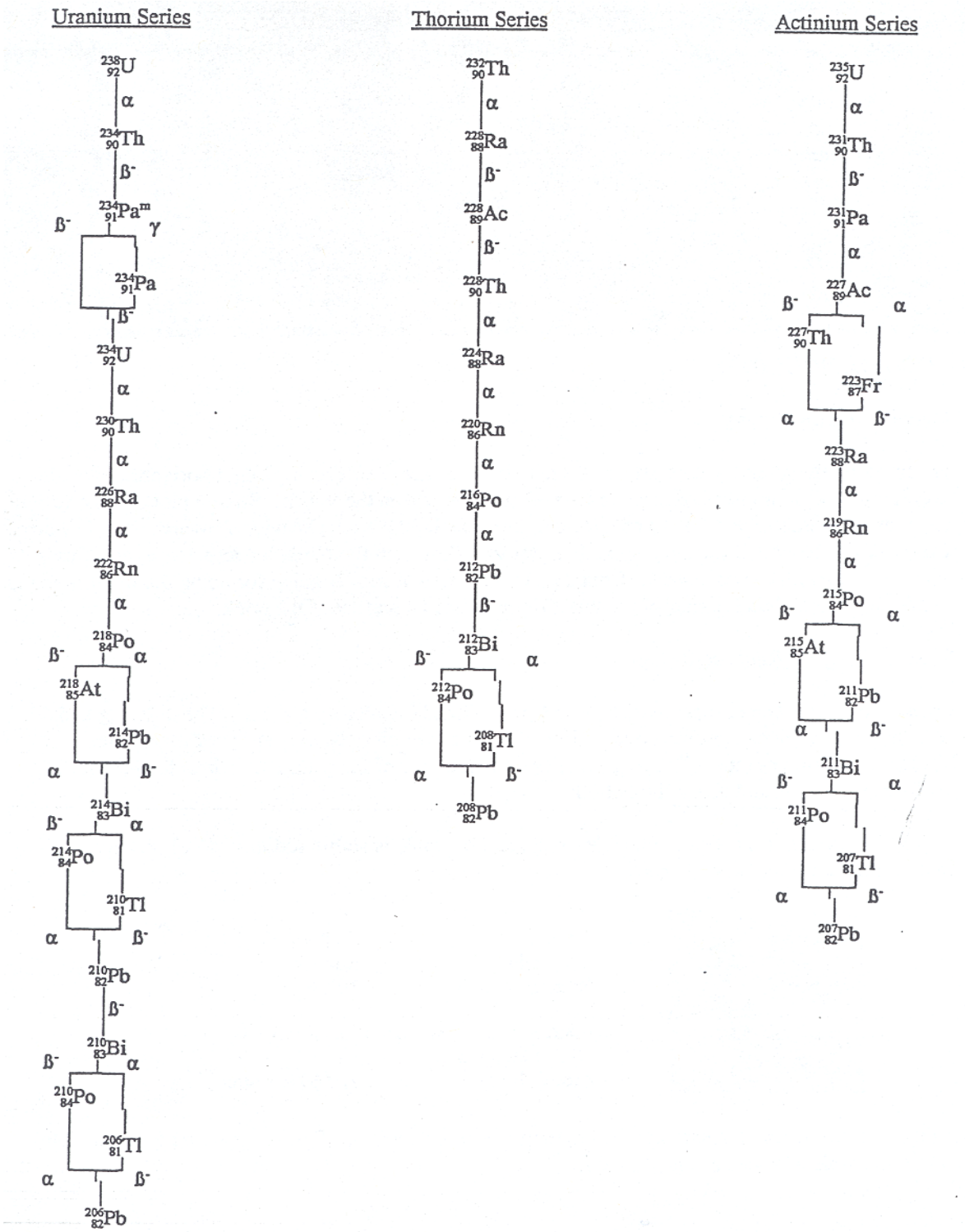
In each series, there is a "seesawing" in the transmutation chain between decreasing the atomic number by two with an emission and increasing it by one with β^- emission. Each series has an isotope of radon (historically known as *radon* [$^{222}_{86}$Rn], *thoron* [$^{220}_{86}$Rn], and *actinon* [$^{219}_{86}$Rn], respectively) as a member of the series. All isotopes of radon are radioactive and are gases at standard temperature and pressure. Each series ends in a different stable isotope of lead ($^{206}_{82}$Pb, $^{208}_{82}$Pb, and $^{207}_{82}$Pb, respectively).

Figure 3 shows the three natural decay series.

Artificial Series

There is also a fourth series, the **neptunium series**, named after its longest-lived member. Actually, the neptunium series has been artificially produced and no longer occurs in nature, but it is assumed that it did occur in nature at one time and has become extinct because of the relatively short half-lives involved. The longest-lived radionuclide in the series is $^{237}_{93}$Np with a half-life of 2.2E06 years. Assuming the age of the earth is 2.2E09 years, this would indicate that, from the time of creation, ^{237}Np has undergone 1,000 half lives decay. The fraction of a radionuclide remaining after 1,000 half-lives would be astronomically small—on the order of 10^{-300}. It is obvious, therefore, why it would be difficult to find traces of neptunium and its descendants in nature.

Figure 3. Natural Decay Series



1.06.09 ***Given a nuclide, locate its block on the Chart of the Nuclides and identify the following:***

- **a. Atomic number**
- **b. Atomic mass**
- **c. Natural percent abundance**
- **d. Stability**
- **e. Half-life**
- **f. Types and energies of radioactive emissions.**

1.06.10 ***Given the Chart of Nuclides trace the decay of a radioactive nuclide and identify the stable end-product.***

CHART OF THE NUCLIDES

General Arrangement

In arranging the nuclides in chart form, the number of neutrons (N) is plotted horizontally on the x-axis against the number of protons (atomic number, Z) on the y-axis. Such a plot at once reveals the continuity in composition in progressing from the lighter to the heavier elements. The full-size **Chart of the Nuclides** (poster) is much easier to follow than the **Nuclides and Isotopes** volume that contains all the material from the chart in book form. A guide for using the chart is found in the lower right-hand corner of the chart or on pages 18 and 19 of the book.

Specific Nuclide Representation

Each specific nuclide is represented in the Chart of the Nuclides by a block. The coloring and labeling of each block specifies certain information concerning the properties of the nuclide. Values for atomic number (Z) are given along the left side of the grid, and values for number of neutrons (N) are found along the bottom.

A **grey block** denotes a *stable nuclide.* A typical example is stable sodium, ($^{23}_{11}$Na). A key to the listed data within the block is shown below.

^{23}Na 100 φγ (40 + 13), 32 22.989767 amu

Nuclide: Sodium-23
Grey color: stable
Percent Abundance: 100%

Neutron activation cross section in barns—
(n, γ) interaction
Atomic mass: 22.989767 amu

Unlike sodium, most elements have more than one stable isotope. For example, magnesium (Mg) has three stable isotopes as shown below.

	^{24}Mg	^{25}Mg	^{26}Mg
Percent abundance	78.99	10.00	11.01
Atomic mass (amu)	23.985042	24.985837	25.982594

A white block denotes an *artificially produced radioactive* nuclide. A typical example is $^{59}_{26}$Fe.

A key to data listed within the block is shown below:

^{59}Fe	- nuclide
45.51 d	- half-life (yellow color. 10 to 100 days)
β^- .466,.271	- beta energies in MeV
ϒ1099.2,1291.6,	- gamma energies in keV
E 1.56	- disintegration energy in MeV

A white block with a **black triangle in the lower right hand corner** denotes an artificially produced radionuclide that results from slow neutron fission (fission product). An example follows.

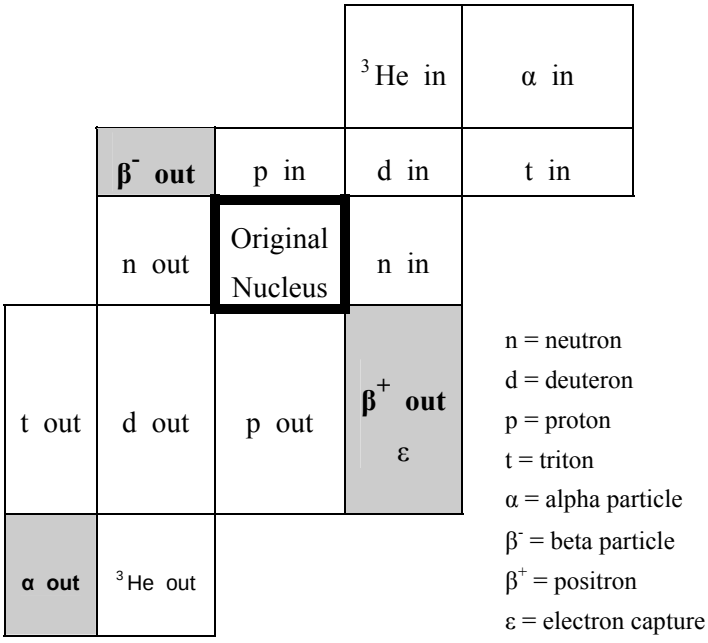
^{90}Sr	- nuclide
29.1 a	- half-life
β^- .546	- beta energies in MeV
no ϒ	- no associate gamma emission
E .546	- beta decay energy in MeV

A **grey block with a black bar across the top** denotes a long-lived, *naturally occurring radioactive* isotope. $^{238}_{92}U$ is a good example.

^{238}U	- nuclide
99.2745	- percent abundance
4.47E9 a	- half-life
α 4.197,4.147	- mode of decay, radiation and energy
γ 49.6	- gamma energy in keV
238.050785	- isotopic mass in amu

Depicting Nuclear Processes

As a result of decay, radio nuclides shift from block to block within the Chart of the Nuclides. The diagram below (taken from the Guide for using the Chart of the Nuclides) shows the relative locations of the products of various nuclear processes.



As can be seen, the relative locations (displacements) of the primary modes of decay are:

Alpha (α)	down 2, left 2 (↓↓, ←←)
Beta (β^-)	up 1, left 1 (↑ ←)
Positron (β^+)/EC	down 1, right 1 (↓ →)

Displacements can also occur as a result of nuclear reactions brought about through bombarding given nuclides with various nuclear particles or gamma photons. These changes are depicted in the "Guide for using the Chart of the Nuclides."

Chart of the Nuclides Summary

The Chart of the Nuclides provides considerable information about the behavior of nuclides. There is continuity in composition of the nuclides. For example, a line drawn through the stable nuclides forms a rather smooth curve extending from the lower left to the upper right corner of the Chart of the Nuclides.

Nuclides below this line are characterized by having an excess of neutrons and will, in general, be beta particle emitters.

Nuclides above this line are characterized by having an excess of protons and will, in general, decay by positron emission or electron capture.

Nuclides lying beyond the line of stability will, in general, demonstrate a tendency to seesaw between alpha decay and beta decay. All nuclides, if followed through their various decay schemes, will eventually end in a grey box (stable isotope).

The Chart presents in compact style much valuable information concerning the properties of the nuclides. These data include for:

1. Stable nuclides
    a. Relative abundance
    b. Cross section for activation.
2. Radioactive nuclides
    a. Types of emissions
    b. Energy of emissions
    c. Half-life.

1.06.11 Define the following units:

a. curie

b. becquerel

Radioactivity and Radioactive Decay

UNITS OF ACTIVITY

The rate of decay of a radioactive substance constitutes the quantity of radioactivity, or *activity*, in that substance. The definition of activity refers to the number of transformations (disintegrations) per unit time. Because the fundamental unit of time is the second, the quantity activity is measured in disintegrations per second, or dps. Because the second is a very short time period in which to make a measurement, activity is measured in units of disintegrations per minutes, or dpm. The SI unit of activity is the becquerel (Bq), while the historical unit is the curie (Ci). Each will be discussed below.

The Curie

Before the large-scale production of artificial radioisotopes, radium had become a standard of comparison for radioactivity measurements. Originally, the unit curie, (Ci), applied only to Radium-226. Named for Marie Curie, this unit was based on the disintegrations per second (dps), occurring in the quantity of Radon-222, a gas, in equilibrium with 1 gram of Radium-226. In that case about 0.66 mm^3 of radon (17.74×10^{15} nuclei of ^{222}Rn) will be in equilibrium with 1 gram of radium (2.66×10^{21} atoms of ^{226}Ra), and about 37 billion of radon nuclei will disintegrate each second (~3.7×10^{10} dps / Ci).

In 1930, the International Radium Standard Commission extended the definition to include that quantity of any radioactive decay product of radium that underwent the same number of dps as 1 gram of radium. It avoided specifying the figure exactly, so for some years the exact value of the curie varied with each successive refinement in the measurement of the decay constant or the atomic weight of radium.

In 1950, the International Joint Commission on Standards, Units, and Constants of Radioactivity redefined the *curie* by accepting exactly 37 billion dps as a curie of radioactivity regardless of its source or characteristics. Current regulations define the curie (Ci) as exactly 3.7×10^{10} dps disintegrations per second (2.22×10^{12} dpm).

Because the curie represents a very large amount of activity, often smaller and more convenient subunits are used:

Table 5. Curie Subunits

Unit	Abbr.	dps	dpm
curie	Ci	3.7E10	2.22E12
millicurie	mCi	3.7E7	2.22E9
microcurie	μCi	3.7E4	2.22E6
nanocurie	nCi	3.7E1	2.22E3
picocurie	pCi	3.7E-2	2.22

The Becquerel

The SI derived unit of activity is the *becquerel* (Bq) and is that quantity of radioactive material in which one atom is transformed per second or undergoes exactly 1 disintegration per second (1 dps). Because the becquerel is a rather small unit, metric prefixes are often applied to aid in designating larger amounts of activity:

Table 6. Becquerel Superunits

Unit	Abbr.	dps	dpm
becquerel	Bq	1	60
kilobecquerel	kBq	lE3	6E4
megabecquerel	MBq	lE6	6E7

The relationship between the becquerel and curie is:

1Bq =1 dps = 2.7E-11 Ci 1 Ci = 3.7E10 dps = 3.7E10 Bq

Using unit analysis and conversion, activity measurements given in dps, dpm, or curies can be converted to becquerel.

1.06.12 Define specific activity.

SPECIFIC ACTIVITY

Specific activity is defined as the activity per unit mass of a radioactive substance and is reported in units such as curies per gram (Ci/g) or becquerel per kilogram (Bq/kg). Recall that the curie, although, originated from the number of emanations from 1 gram of radium every second, is defined as exactly 3.7×10^{10} dps, regardless of the radioactive isotope. This means that the specific activity of radium would not be exactly 1 Ci/g, but ~0.988 Ci/g.

When applied to radio-nuclides, the unit curie does not make apparent what mass of a radioactive material generates 1 Ci of activity. Because 1 curie of activity is 3.7E10 dps, the mass of the material required to produce this number of dps will be a function of the decay rate of the atoms of the material (i.e., the disintegration constant $\lambda = 0.693 / t_{1/2}$) and of the number of atoms of the material per gram (i.e., *gram atomic mass /weight).* For example, a curie of pure ^{60}Co ($t_{1/2}$ = 5.27 years) would have a mass less than 0.9 milligrams, whereas a curie of natural ^{238}U ($t_{1/2}$= 4.5E9 years) would require over 2 metric tons of the metal. Obviously, the shorter the half life of a radionuclide (it decays faster,) the greater is its specific activity.

1.06.13 Define half-life.

THE RADIOACTIVE DECAY LAW

The activity of any radioactive material decreases or decays, at a constant rate, that is a characteristic of that particular radionuclide. No known physical or chemical agents, such as temperature, pressure, dissolution, or combination, may be made to influence this rate. The rate may be characterized by observing the fraction of activity that remains after successive time intervals.

For convenience we choose a fraction that is easy to work with, 1/2. In using this fraction, we can observe the decay of a radionuclide with the passing of time. We can observe how long it takes for the activity to be reduced to one half of the activity. This time that is required for the activity present to be reduced to one-half we call the *half-life.* If successive half-lives are observed, we can see a reduction each time by a fraction of one-half, and the effect will be cumulative. In other words, one half-life reduces to $(1/2)^1$; two half-lives reduces to $1/2 \times 1/2 = (1/2)^2$ or 1/4; three half-lives will reduce to $1/2 \times 1/2 \times 1/2 = (1/2)^3$ or 1/8, etc. In the general case the fraction of activity remaining after any number of half lives will be $(1/2)^n$, where n is the number of half-lives that have elapsed. To put it still another way, the reduction in activity occurs at an exponential rate, which we have expressed as the power of 1/2.

In Figure 4, we can see that as time passes, radioactive decay occurs at an exponential rate. In using the half-life for our time value, we express this exponential function as $(1/2)^n$. Beginning at the instant chosen as the starting point, we have 100% of the activity, because no time has elapsed, and the number of half-lives is zero ($n = 0$). If we use t to represent time, at this point, then, $t = 0$.

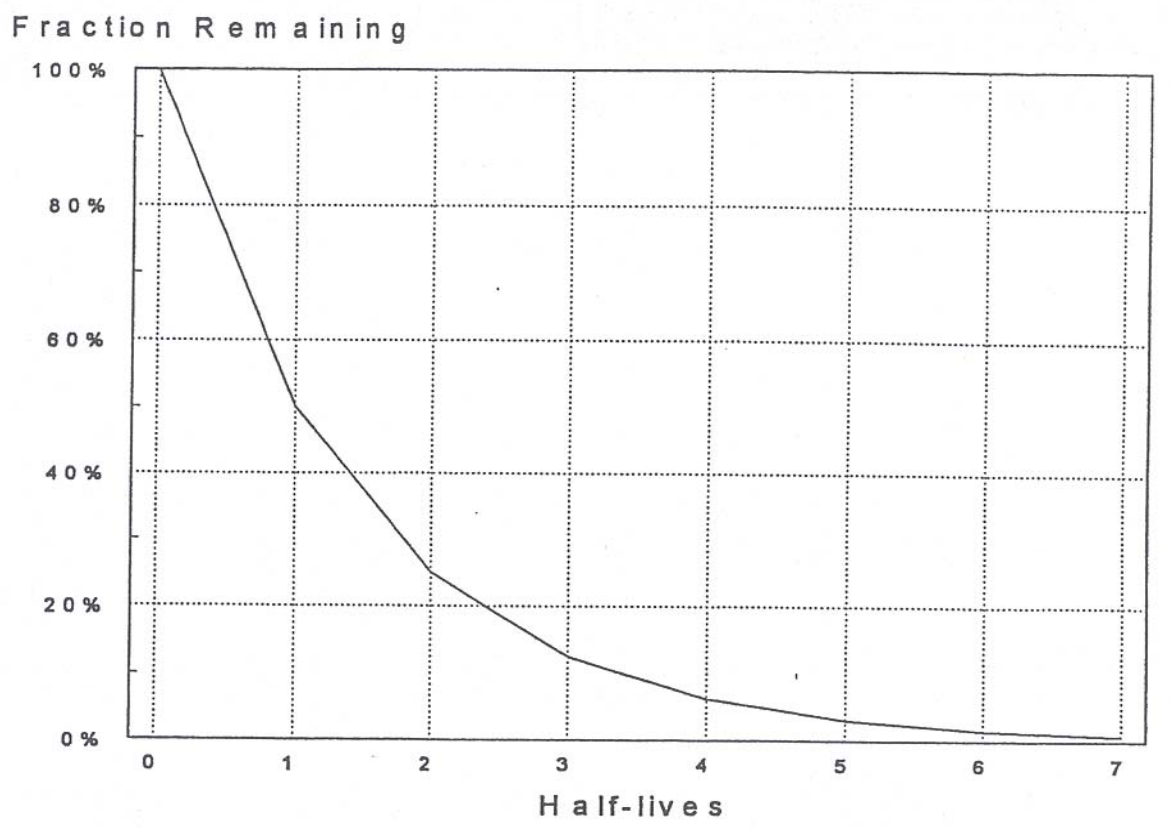


Figure 4. Radioactive Decay (Linear Scale)

If we let $T_{1/2}$ represent the half-life, then, after one half-life, $t = T_{1/2}$, and $n = 1$. This demonstrates that n represents the ratio of time versus the half-life. Mathematically, this is expressed as:

$$n = \frac{t}{T_{1/2}}$$

where:

n = number of half-lives

t = time elapsed

$T_{1/2}$ = half-life

Obviously, the units of t must be the same as the time units of $T_{1/2}$ in order to determine the value of n. For example, if the half-life of a certain radionuclide is 10 hours, and we allow 4 hours to elapse, the number of half-lives would be 4/10 = 0.4, or 0.4 half-lives. The fraction remaining at that instant where t = 4 hours would be:

$$\left(\frac{1}{2}\right)^{\frac{4}{10}} = \left(\frac{1}{2}\right)^{0.4} = 0.7578$$

The activity at the instant where $t = 0$ is the initial or original activity, represented as A_o. The activity at any time t after 0 we will denote as A_t. The value of A_t at any time t will be the fraction remaining times A_0. The fraction remaining is determined from the number of half-lives that have passed. A useful "rule of thumb" to remember is that seven half-lives will reduce any activity to less than 1% of its original value. Using a proportion we can see the relationship between the two activities:

$$\frac{A_0}{A_t} = \frac{1}{(1/2)^n}$$

By cross-multiplying, we obtain the equation for determining the remaining activity:

$$A_t = A_0 (1/2)^n$$

For example, if the initial activity of the radionuclide mentioned above was 52 μCi, then the activity after 4 hours would be:

$$A_t = 52\,\mu Ci\left(\frac{1}{2}\right)^{\frac{4}{10}}$$

$$A_t = 52\,(0.7578)$$

$$A_t = 39.4\,\mu Ci$$

Remember that we stated earlier that radioactive decay is an exponential process. Recall also that a logarithm is, by definition, an exponent. If we were to plot the activity on a logarithmic scale against the time on a linear scale, the resulting curve should be a straight line. Figure 5 illustrates that this is the case.

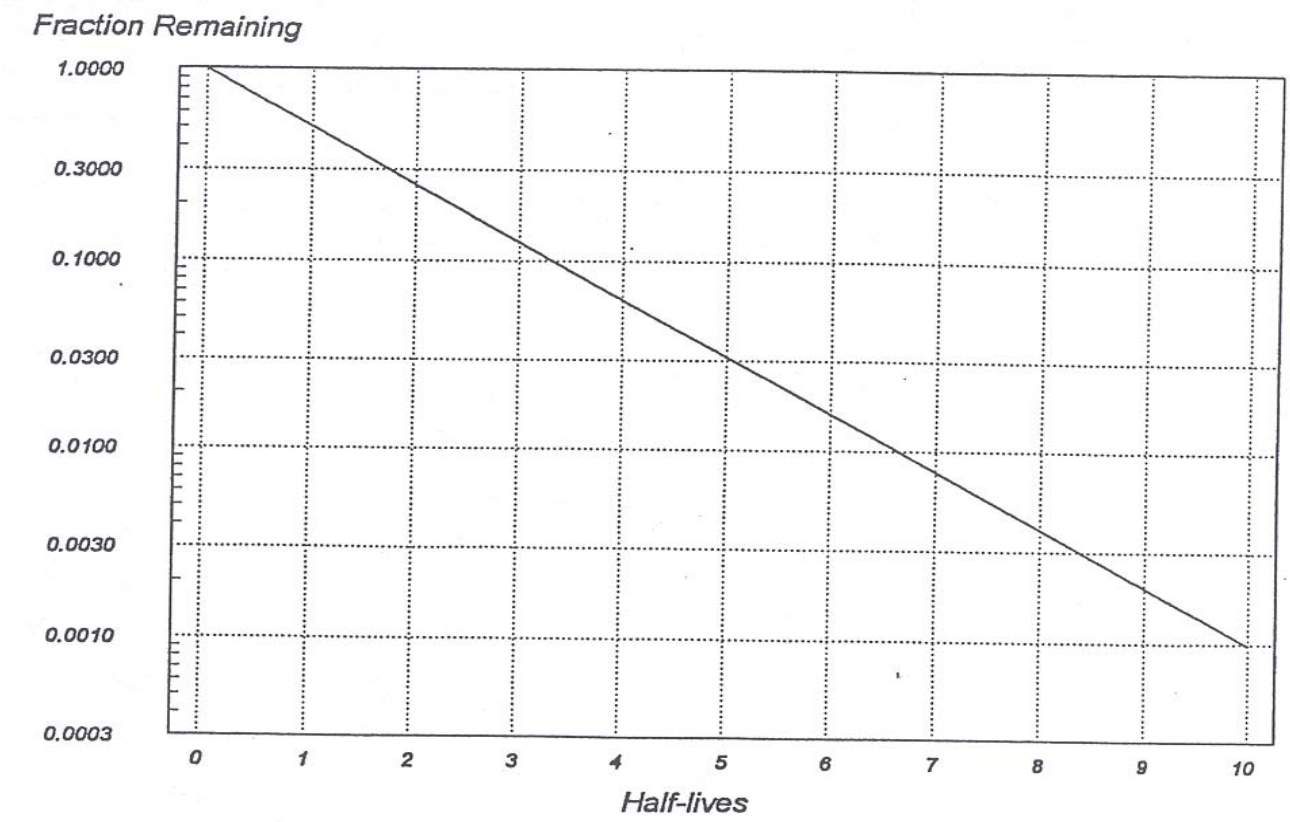


Figure 5. Radioactive Decay (Semi log Scale)

This graph shows us that the rate of decay does in fact occur at a constant rate. As time elapses from the starting instant, the activity is reduced thereafter at the constant rate of disintegration for the particular radionuclide involved, which we represent by the Greek letter λ (pronounced "lambda"). In the graph above, the reduction of activity is now a logarithmic (exponential) function of $(1/2)^n$. Because n is the ratio of t versus $T_{1/2}$, the fraction remaining after time t will be less than 1, resulting in a negative natural-logarithmic value (ln 1/2 = -ln 2 = -0.693). (Using calculus, the natural logarithm [ln] resulted from the integration of the first equation devised by Rutherford.) The fraction remaining will be a function of the decay constant (λ) and the time (t). If we then relate the decay constant to the half-life, λ will be a composite of the natural log of 2 and the half-life. Because the process leads to a decrease in activity, the exponent will be represented by $-\lambda t$. Therefore, the decay constant itself will represent:

$$\lambda = \frac{ln\,2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

Thus, the decay constant is the fraction that disintegrates per unit time (reciprocal time). If the half-life is, for example, in seconds then λ will be in sec^{-1}.

1.06.14 Calculate; activity, time of decay, and radiological half-life using the formula for radioactive decay.

The equation for activity using the decay constant will be:

$$A_t = A_0 e^{-\lambda t}$$

In this equation, the base of the natural log is raised to a power, which includes the -ln 2. The result of this equation is exactly the same at that which results from the equation using $(1/2)^n$. It is simply a different way of expressing the decrease in activity with the passage of time as a result of radioactive decay.

By using the data in the prior example, the equation would be:

$$A_t = 52\, e^{\left(\frac{-\ln 2}{10}\right)4}$$

$$A_t = 52\ e^{-0.277}$$

$$A_t = 52\,(0.7578)$$

$$A_t = 39.4\ \mu Ci$$

Example: Given 10 mCi of ^{32}P, which has a half-life of 14.2 days, find the quantity remaining after 60 days.

$$A_t = 10\, e^{\left(\frac{-\ln 2}{14.2}\right)60}$$

$$A_t = 10\ e^{-2.93}$$

$$A_t = 10\,(0.0534)$$

$$A_t = 0.534\, mCi$$

By algebraic manipulation other variables in this equation can be solved for if the other values are known. One example would be calculating the original activity based on the current activity, decay constant, and elapsed time.

Practice Problems

1. A Phosphorous-32 source has a half-life of 14.28 days and had an activity of 75,000 dpm as of 12/2/92. What was the activity as of 12/28/92?

2. A 55 nCi ^{90}Sr source was assayed on 6/1/88. What would the activity be on 6/1/93? (The half-life of ^{90}Sr is 29.1 years)

3. A 60 mCi iodine solution of ^{131}I was created and then left on a laboratory shelf for 2 weeks before it was used. What was the activity of the solution at the time it was used? (Iodine-131 has a half-life of 8.04 days)

4. A radon air sample was collected and then counted 4 hours later. If the sample count showed an activity of 5E4 pCi, what was the activity on the sample at the time it was collected? (Radon-222 has a half-life of 3.8235 days)

5. A 10.5 Ci-60 Co radiography source was prepared 3 years ago, having a half-life of 5.271 years. What is the activity today?

6. A pure alpha source reads 244,000 dpm today. It is a ^{210}Po source which has a half-life of 138.38 days. If the source was manufactured a year ago, what the activity at the time it was manufactured?

7. A ^{137}Cs source has an activity of 750 mCi, with a half-life of 30.17 years. How long will it take for the source to be read less than 100 mCi?

8. An air sample was collected in a thorium storage building and was counted immediately, yielding 2.5E3 pCi/l. The sample was recounted 5 minutes later, giving an activity of only 59.4 pCi/1. What is the half-life and the most likely isotope on the sample?

SERIES DECAY

"Series Decay" concerns the mathematical relationship of quantities of activity present when two or more radio-nuclides exist in a decay chain. Examples of a decay chain are the natural decay series, or a two-step fission product decay series such as:

$$^{90}\text{Sr} \rightarrow \beta^- + {}^{90}\text{Y} \rightarrow \beta^- + {}^{90}\text{Zr (stable)}$$

The relationship between three or more radio-nuclides is described by H. Bateman. The solution, while straightforward, is quite involved. A two-step relationship (parent-daughter) can be readily derived and is reasonably easy with which to work.

PARENT-DAUGHTER RELATIONSHIPS

In a radioactive decay series, the decay of the parent nuclide produces a daughter product and radiation is emitted. The daughter nuclide also produces radioactivity when it decays, as does each successive daughter in the chain until stability is reached, resulting in total collective activity. The activity contributed from the parent versus the daughters will vary depending on the half-life of the parent and the half-lives of the daughters. When the amount of activity being produced is the same as the amount that is decaying, a state of *equilibrium is* said to exist. There are several types of equilibrium, depending on how the half-life of the daughter compares to the half-life of the parent.

Secular Equilibrium

In secular equilibrium, the half-life of the parent is much longer than the half-life of the daughter. When in equilibrium, the activity of the daughter is equal to the activity of the parent. Initially, the majority of the activity will be contributed by the parent. As more and more of the parent nuclide decays, the amount of activity contributed by the daughter will increase.

Transient Equilibrium

In transient equilibrium, the half-life of the parent is somewhat longer than that of the daughter. In a freshly purified parent fraction, the daughter activity builds up, then, it decays with the same rate of decay as the parent.

No Equilibrium

When the half-life of the parent is shorter than that of the daughter, the two never reach a state of equilibrium. Figure 6 illustrates this.

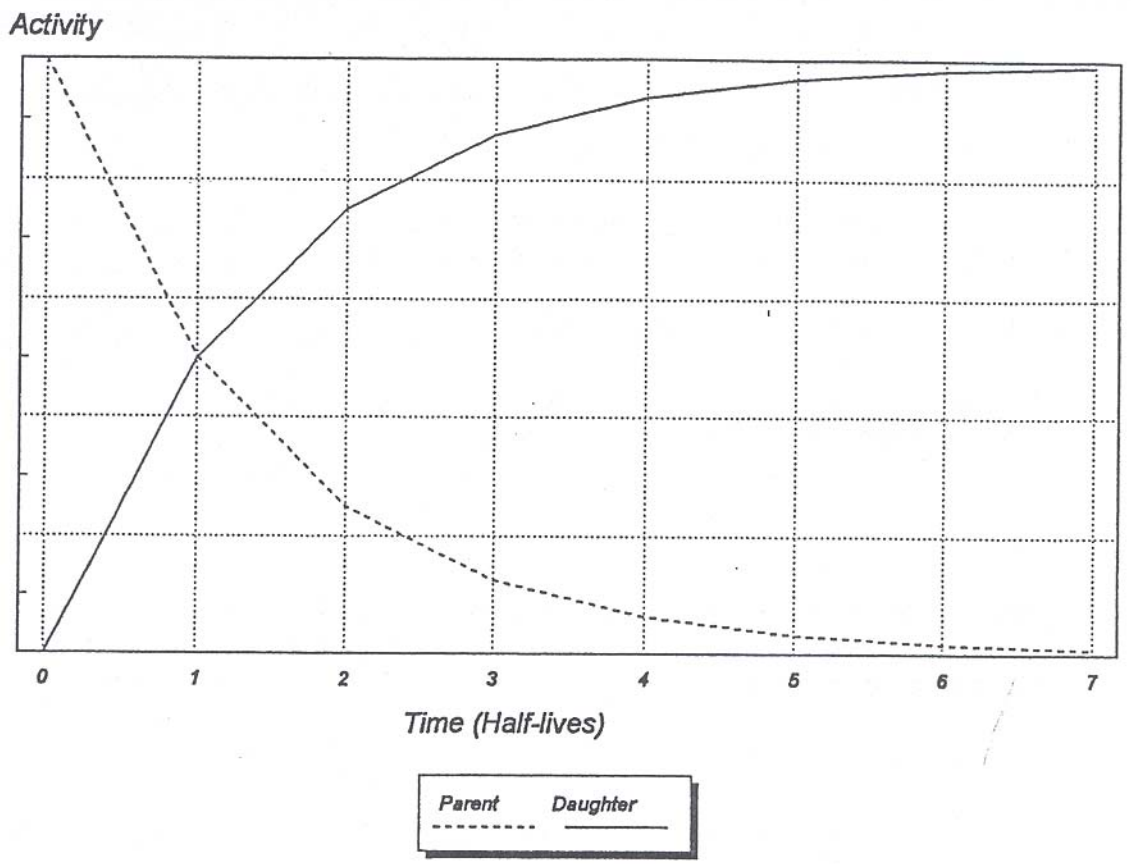


Figure 6. No Equilibrium

1.06.15 Define the following:

a. Exposure
b. Absorbed dose
c. Equivalent Dose
d. Radiation Weighting factor.

1.06.16 Define the following units:

a. Roentgen
b. Rad/gray
c. Rem/sievert.

RADIATION DOSIMETRY TERMINOLOGY

During the early days of radiological experience, there was no precise unit of radiation dose that was suitable either for radiation protection or for radiation therapy. For example, one early unit devised was the "skin erythema unit," where allowable dose was the amount required to produce skin reddening. Because of the great energy dependence of these various units, as well as other inherent defects, none of these was useful for radiobiological studies or for radiation protection. Furthermore, because the fraction of the energy in a radiation field that is absorbed by the body is energy dependent, it is necessary to distinguish between radiation *exposure* and *absorbed dose.*

Exposure (X)

Exposure is a measure of the ability of photons (X and gamma) to produce ionization in air. Traditionally, the unit of exposure is the roentgen (R). The unit is defined as the sum of charge per unit mass of air; that is:

1 roentgen = 2.58E-4 coulombs/kg of air

Note: The roentgen was originally defined as the quantity of X or gamma radiation that will produce ions carrying 1.0 electrostatic unit (esu) of electrical charge in 1 cubic centimeter of dry air under standard conditions (0 ^{o}C, 1 atmosphere of pressure).

There is no SI unit defined for exposure. This was done intentionally to discourage further use of this unit. The definition of the roentgen places severe limitations on the interpretation of radiation measurements because it describes only the amount of ionization caused by x-ray or gamma radiation (E < 3 MeV) in air. Another unit must be used to describe the amount of ionization caused by any radiation in any material.

Absorbed Dose (D)

Units of dose measure the amount of radiation energy absorbed or deposited per unit of mass. The "energy deposited" by radiation is an expression for the "amount of ionization caused" and both expressions mean the same thing. For example, as a charged particle passes through air, it creates ion pairs. The creation of each of these pairs requires about 33.9 eV. The radiation, therefore, gives up this amount of energy to the air each time it creates an ion pair. In other words, it deposits energy in the air.

The Rad

The old (CGS) unit of absorbed dose is the *rad*, which is an acronym for **R**adiation **A**bsorbed **D**ose. The unit rad can be applied to all types of radiation and is defined as the deposition by any radiation of 100 ergs of energy in 1 gram of any material.

Note: For simplicity purposes, 1 rad of photons is usually considered to be equivalent to 1 R. The actual physical relationship is such that an exposure of 1 R would produce an absorbed dose of 0.87 air rads. This means that 1 R = 87 ergs/g.

The Gray

The SI Derived unit of absorbed dose is the *gray* (Gy), equivalent to the deposition of one joule of energy per kilogram (1 J/kg). The relationship between the gray and the rad is that 1 Gy = 100 rad:

$$1\,Gy = \frac{1J}{kg} \times \frac{1E7\,ergs}{1J} \times \frac{1\,kg}{1E3\,g} \times \frac{1\,rad}{100\,ergs/g} = 100\,rad$$

Although the rad and gray are measures of ionization produced, they do not give any information about the biological effects of the radiation that is absorbed. It is meaningful to emphasize that the energy deposited by the radiation (as a result of the ionization) is the quantity that is actually measured in rad units. Thus, the amount of ionization produced in the detector of a radiation detection instrument can be related to the energy absorbed and expressed by the instrument meter in the unit rad or rad/hr.

Radiation Weighting Factor (w_R)

A *radiation weighting factor* is used to relate the absorbed dose of various kinds of radiation to the biological damage caused to the exposed tissue or organ. A radiation weighting factor is necessary to relate the effects of radiation because the same amounts absorbed (energy per kilogram of tissue or organ) of different kinds of radiation cause different degrees of damage. The radiation weighting factor converts the absorbed dose to equivalent dose in units of rem (discussed below) to a common scale that can be added with and compared to damage caused by any kind of radiation. The radiation weighting factor is a conversion factor used to derive the equivalent dose from the absorbed dose and is expressed as:

$$H_T = D_{T,R} \times w_R$$

where:

H_T = equivalent dose

$D_{T,R}$ = average absorbed dose in a tissue or organ

w_R = radiation weighting factor

There is a radiation weighting factor associated with each specific type and energy of radiation. By knowing what type and energy of radiation is present, we can determine the radiation weighting factor and relate the absorbed dose to the equivalent dose. A high radiation weighting factor indicates that type of radiation has a greater biological risk or greater effect than radiation with a lower radiation weighting factor for the same absorbed dose.

Table 7. Radiation Weighting Factors

Radiation Type	QF
Photons, electrons, and muons	1
Neutrons, energy <10 keV	5
Neutrons, energy 10 keV to 100 keV	10
Neutrons, energy >100 keV to 2 MeV	20
Neutrons, energy >2MeV to 20 MeV	10
Neutrons, energy >20 MeV	5
Protons, other than recoil atoms, energy >2MeV	5
Alpha particles, fission fragments, heavy nuclei	20

For example, an absorbed dose of 100 millirad thermal neutron would be converted to an equivalent dose as follows:

$$100 \text{ mrad } (n_t) \times 3 = 300 \text{ mrem}$$

The radiation weighting factor can also be applied to an absorbed-dose rate (rad/hr) in order to obtain an equivalent dose rate (rem/hr).

Equivalent Dose (H_T)

A measurement of the equivalent dose is calculated as the absorbed dose multiplied by the radiation weighting factor, which relates the relative risk from the type of radiation absorbed to the risk from the same dose of X or gamma radiation.

The Rem

The old unit of equivalent dose is the rem, which is an acronym for Roentgen Equivalent Man. The rem was the quantity of ionizing radiation whose biological effect (in man) is equal to that produced by 1 roentgen of x-rays or gamma radiation. The equivalent dose in rem is numerically equal to the absorbed dose in rad multiplied by the radiation weighting factor.

$$\text{rem} = \text{rad} \times w_R$$

The Sievert

The SI Derived unit of equivalent dose is the *sievert* (Sv). The equivalent dose in sieverts is equal to the absorbed dose in grays multiplied by the radiation weighting factor:

$$\text{sievert} = \text{gray} \times w_R$$

Because, 1 gray is equal to 100 rad, it follows that:

$$1 \text{ Sv} = 100 \text{ rem}$$

It should be emphasized that the relative risk from 1 rem equivalent dose from neutrons is the same as the risk from 1 rem equivalent dose from gamma or any other radiation. Use of equivalent dose units for recording personnel radiation exposure permits us to add exposures from various types of radiation and get a total equivalent dose, which is proportional to the risk.

Table 8 provides a summary of these dosimetry units and their associated values.

Table 8. Dosimetry Terminology Summary

Term	Unit	Abbr.	Value(s)	Medium	Radiation (s)
Exposure	roentgen	R	1ESU/cc 87 ergs/g	dry air at STP	X,γ
	—	X	2.58E-4 C/kg	air	
CGS ***Absorbed Dose (D)***	Radiation Absorbed Dose	rad	100 ergs/g	any	all
SI	gray	Gy	1 J/kg 100 rad		
Equivalent Dose (H_T) SI	Roentgen Equivalent Man	rem	equivalent biological damage as 1 Roentgen	tissue	all
	sievert	Sv	100 rem		

ANSWERS TO ACTIVITY PRACTICE PROBLEMS

1. 21,230.9 dpm
2. 48.8 nCi
3. 17.95 mCi
4. 51534 pCi
5. 7.1 Ci
6. 1.52E6 dpm
7. 87.7 years
8. 55.6 seconds – Radon-220 (Thoron)