CHAPTER 2

FUNDAMENTAL RADIATION CONCEPTS

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I. WHAT IS RADIATION?

Radiation is defined as energy that travels through space or matter in the form of a particle or wave. It can be produced in one of two ways: by radioactive decay of an unstable atom (radionuclide), or by the interaction of a particle with matter. Some attributes of radioactive decay are that it is spontaneous and random, and the type of radiation emitted depends on the specific radionuclide. Radiation emission as the result of an interaction, on the other hand, depends on both the incoming particle and the material it hits, and is theoretically predictable if enough information is known. (In reality, it is impossible to obtain enough information to make predictions about radiation emission from a single incoming particle, but it is possible to make statistical predictions about large numbers of particles.) Radioactive decay and interactions will be discussed in more detail in the following sections.

Radiation is described by its type and energy. The types of radiation fall into two main categories: particulate and electromagnetic. Particulate radiation consists of particles that have mass and energy, and may or may not have an electric charge. Examples of particulate radiation include alpha particles, protons, beta particles, and neutrons. Electromagnetic radiation, on the other hand, consists of photons that have energy, but no mass or charge. A photon, as described by quantum theory, is a "particle" or "quantum" that contains a discrete quantity of electromagnetic energy which travels at the speed of light, or 3×10^8 meters per second. A photon is sometimes described as a “packet of light”. Visible light, ultraviolet light, x-rays, and gamma rays are all photons.

The most common unit of energy used to describe radiation is the electronvolt (eV). An electronvolt is the amount of kinetic energy an electron gains when accelerated through a potential difference of one volt. The conversion to SI units is $1 \text{ eV} = 1.6 \text{x} 10^{-19}$ joules. An eV is a very small unit of energy, so in many applications, it is more common to use kilo-electronvolts (1 keV = 1000 eV) or mega-electronvolts (1 MeV = 1,000,000 eV).

Radiation can be either ionizing or non-ionizing, depending on its energy and ability to penetrate matter. Non-ionizing radiation, such as visible light, is not harmful. Only ionizing radiation is discussed in this course. Ionization is discussed in more detail on page 11.

II. THE RADIOACTIVE ATOM

All matter is composed of atoms. The atom contains a nucleus, consisting of protons and neutrons, with electrons revolving in orbits about the nucleus. Electrons carry a negative charge, protons carry a positive charge, and neutrons have no electrical charge. An atom normally has one electron in orbit for each proton in the nucleus, leaving the atom electrically neutral. An element is a type of atom distinguished by its number of protons (e.g. an atom of the element hydrogen always has one proton; an atom of the element helium always has two protons, etc).

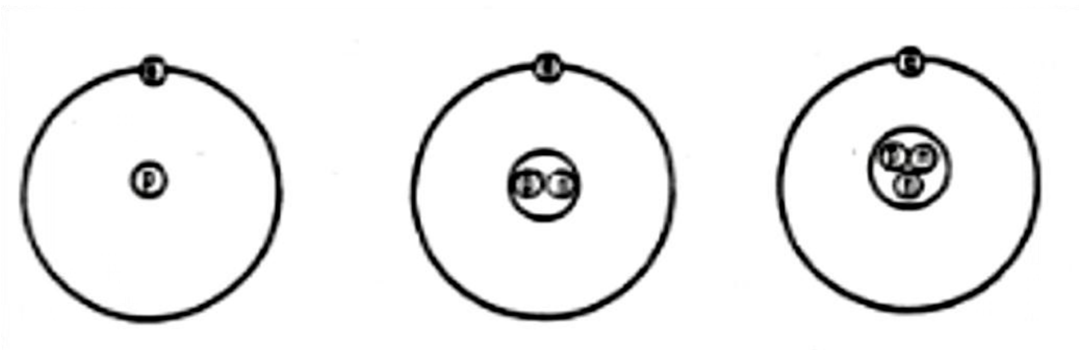
The atomic structure of an element is denoted as $^{A}_{Z}X$

where: X is the chemical symbol of the element.

Z is the atomic number, defined as the number of protons in the nucleus. This determines the chemical identity of the element.

A is the mass number, defined as the sum of the number of protons and neutrons in the nucleus. Thus, A minus Z gives the number of neutrons. An element may have different numbers of neutrons and still be chemically the same.

Each individual arrangement of protons and neutrons is referred to as a nuclide. Nuclides which have the same number of protons are called isotopes. Shown below are examples of isotopes of hydrogen:



$^{1}_{1}H$ *Hydrogen* $^{2}_{1}H$ *Deuterium* $^{3}_{1}H$ *Tritium*

Many nuclides (but not all) are unstable or "radioactive". In the above example of nuclides, only tritium is radioactive. Radioactivity is defined as the spontaneous disintegration of unstable nuclei, with the resulting emission of radiation that results in the formation of new nuclei. Stability of the nucleus is related to its ratio of neutrons to protons. For low atomic number elements, approximately equal numbers of neutrons and protons in the nucleus are necessary for stability. For elements of higher atomic number, the ratio rises to approximately 1.6 to 1. As a nuclide departs from this stable ratio, changes in the nucleus occur which tend to bring the product to a more stable arrangement. This approach to stability is accomplished by one or more of five (5) "radioactive decay modes".

III. RADIOACTIVE DECAY MODES

A. Beta Minus Decay

When the neutron to proton ratio is too high, a neutron "transforms" into a proton and electron, with the electron being ejected from the nucleus. The ejected electron is called a "beta minus particle" or just "beta particle". Beta particles are not emitted with a single energy but are emitted with a spectrum of energies up to some maximum value. This is due to a division of the total energy of each disintegration between the beta particle and a neutrino, which is another particle that is emitted at the same time as the beta particle. The neutrino has a negligibly small mass and no charge, and it carries off varying amounts of the released energy. It therefore travels great distances, losing little energy in nearby materials and causing no biological damage.

The energy of the ejected beta particle is characteristic of each nuclide and is one criterion used for identification purposes. In general, the average particle energy is about 1/3 of the maximum possible energy.

The generalized atomic equation for beta decay is as follows:

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

X = original (parent) atom
Y = new (daughter) atom
ß⁻ = beta particle (electron)
ν = neutrino

Examples of Beta decay:

$${}^{3}_{1}H \rightarrow {}^{3}_{2}He + 0.0186\ MeV\ \beta^{-}$$

MeV = mega electronvolts
= 1 million electron volts

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + 0.156\ MeV\ \beta^{-}$$

β^{-} = maximum beta particle energy

Note that the term "beta minus decay" is often simplified to "beta decay."

B. Positron/Beta Plus Decay

When the neutron to proton ratio is too low, a proton transforms into a neutron and a positron (beta plus particle), and the positron is ejected from the atom. A positron has a positive charge and the same mass as an electron. The positron behaves exactly as an electron except that when the positron comes in contact with a free electron, the two particles combine and are annihilated. This gives rise to two photons whose energies correspond to the rest mass equivalence of the particles (0.511 MeV/photon). See page 16 for a description of annihilation radiation. Like beta minus decay, the energy released in the decay is split between the positron and a neutrino, so positrons are emitted with a spectrum of energies.

The generalized atomic equation for positron decay is as follows:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^{+} + \nu \qquad \beta^{+} = \text{positron(beta plus particle)}$$

Examples of Positron decay:

$${}^{19}_{10}Ne \rightarrow {}^{19}_{9}F + 2.22\ Mev\ \beta^{+}$$

$${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + 0.544\ Mev\ \beta^{+}$$

C. Alpha Decay

Alpha decay occurs for those nuclides which have an atomic number greater than 82. Such heavy nuclides have no stable configuration of neutrons and protons, and as a result, emit an alpha particle consisting of 2 protons and 2 neutrons. Generally, a series of alpha (as well as beta) decays are required until a lighter, stable element is reached. Unlike beta particles, alpha particles are emitted with a discrete energy.

The generalized atomic equation for alpha decay is:

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

An alpha particle is identical to a helium nucleus, so it is sometimes written ${}^{4}_{2}He^{2+}$ instead of α.

Examples of alpha decay:

$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + 5.3\ MeV\ \alpha$$

$${}^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + 5.59\ MeV\ \alpha$$

D. Electron Capture

In this decay mode, one of the orbital electrons is captured by the nucleus and combines with a proton to form a neutron. Electron capture competes with positron decay when there is a low neutron to proton ratio. If the atom is unable to meet the energy requirements of positron decay, then decay occurs by electron capture. Whenever an atom decays by electron capture, x-rays are emitted that are characteristic of the newly formed nuclide. No particles are emitted during electron capture decay.

The generalized atomic equation for electron capture is:

$$ {}^{A}_{Z}X + {}^{o}_{-1}e \rightarrow {}^{A}_{Z-1}Y + x - rays + \nu $$ e = electron

Examples of electron capture decay:

$$ {}^{54}_{25}Mn + {}^{o}_{-1}e \rightarrow {}^{54}_{24}Cr + 0.835\ MeV\ \ x - rays + \nu $$

$$ {}^{125}_{53}I + {}^{o}_{-1}e \rightarrow {}^{125}_{52}Te + 0.035\ MeV\ \ x - rays + \nu $$

E. Nuclear/Isomeric Transition

When the emission of a particle leaves the product nucleus in a partially excited or "metastable" state (designated with an “m” after the mass number), gamma rays are emitted. The gamma rays carry away the excess energy of the partially excited nucleus after a decay event. Such gamma rays are of a discrete energy and are characteristic of the particular nuclide involved, so they can be used for identification purposes. No particles are emitted, and the nucleus does not change atomic number.

The generalized atomic equation for nuclear transition is:

$$ {}^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma $$ γ= gamma ray

Examples of radionuclides that undergo nuclear transition are shown below. Note that nuclear transition can occur after beta decay, positron decay, alpha decay, or electron capture:

$$ {}^{60}_{27}Co \rightarrow {}^{60m}_{28}Ni\ \ + 0.318\ MeV\ \beta^{-} \rightarrow {}^{60}_{28}N + 1.17\,MeV\,\gamma + 1.33\,MeV\,\gamma $$

$$ {}^{22}_{11}Na \rightarrow {}^{22m}_{10}Ne + 0.543\ MeV\ \beta^{+} \rightarrow {}^{22}_{10}Ne + 1.27\ MeV\,\gamma $$

$$ {}^{226}_{88}Ra \rightarrow {}^{222m}_{86}Rn + 4.47\ MeV\ \alpha + 4.59\,MeV\,\alpha\ \rightarrow {}^{222}_{86}Rn + 0.186\,MeV\,\gamma $$

$$ {}^{125}_{53}I \rightarrow {}^{125m}_{52}Te + x - rays \rightarrow {}^{125}_{52}Te + 0.035\ MeV\,\gamma $$

The Chart of the Nuclides lists all known nuclides and is a useful reference for radioactive decay and energy data (see page 21 for information on obtaining the Chart of the Nuclides).

IV. HALF-LIFE

The half-life of a radioactive substance is the time it takes for half of the atoms to undergo radioactive decay. It can also be defined as the time it takes for the activity of a sample to decrease by half (see section VI). The number of atoms remaining after *n* half-lives is equal to:

$$N = \frac{N_0}{2^n}$$ where N_0 = initial number of atoms.

Thus, for *n* = 1, 1/2 of the initial atoms remain; for *n* = 2, 1/4 remain; for *n* = 3, 1/8 remain, and so on.

V. THE RADIOACTIVE DECAY EQUATION

A radioactive nuclide disintegrates or decays spontaneously at a rate depending on the number of original atoms present and upon its decay constant, lambda (λ). The constant λ is defined as the instantaneous fraction of atoms decaying per unit time. Each radioactive nuclide has its own characteristic decay constant.

The instantaneous time rate of change of the number of atoms, N, for a radionuclide is given by:

$$\frac{dN}{dt} = -\lambda N$$

If we started with N_0 radioactive atoms at some time t = 0, the number of atoms present at some other time N_t can be obtained by integrating:

$$\frac{dN}{N} = -\lambda dt$$

$$\int_{N_o}^{N_t} \frac{dN}{N} = \int_{o}^{t} \lambda dt$$

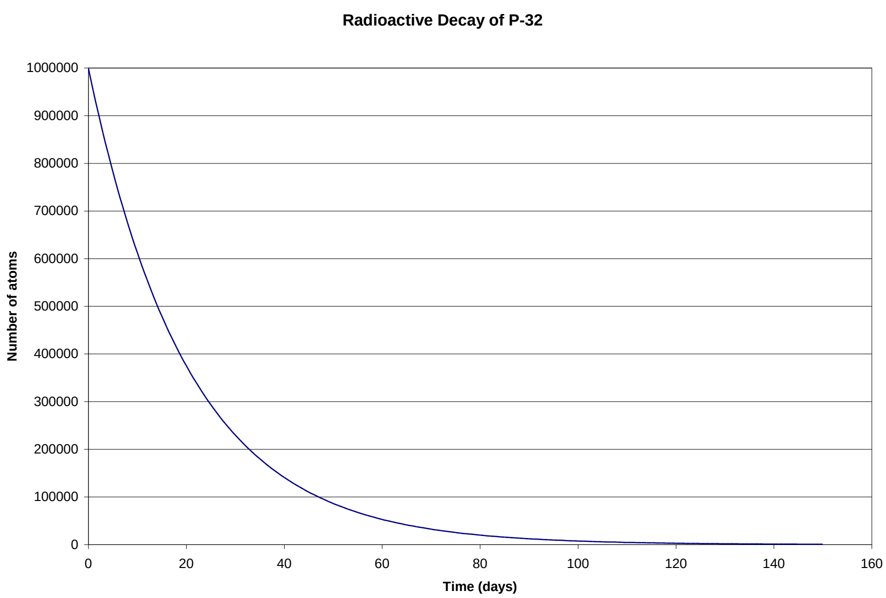
$$1n \left[\frac{N_t}{N_o} \right] = -\lambda t$$

$$\frac{N_t}{N_o} = e^{-\lambda t}$$

$$N_t = N_o e^{-\lambda t}$$

NOTE - the decay time and half-life must be in the same units of time.

The $e^{-\lambda t}$ term indicates that the radioactive atoms decay exponentially. This equation, $N_t = N_o e^{-\lambda t}$, is called the decay equation. The figure below plots the decay equation for P-32, which has a decay constant of 0.049 $^1/_{day}$, starting from one million atoms. The numbers on the y-axis would change depending on the initial number of atoms, and the number on the x-axis would change depending on the radionuclide, but the overall shape of the curve is the same for all radionuclides.



If we were to substitute into the decay equation the time, $T_{1/2}$, it takes for the reduction of a quantity of radioactive atoms to half of the original, we get:

$$N_T = \tfrac{1}{2} N_o$$

$$\tfrac{1}{2} N_o = N_o e^{-\lambda T_{1/2}}$$

$$\tfrac{1}{2} = e^{-\lambda T_{1/2}}$$

$$1n \tfrac{1}{2} = -\lambda T_{1/2} \qquad \left[1n \tfrac{1}{2} = -1n\, 2\right]$$

$$-1n2 = -\lambda T_{1/2}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} \qquad [\ln 2 = 0.693]$$

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

Thus, the decay constant (λ) can be calculated for any radioactive nuclide from its half-life.

VI. RADIOACTIVITY UNITS

The number of atoms, N, remaining at a particular instant in time is given by:

$$A = \lambda N$$

where A is the activity, defined as the instantaneous number of atoms decaying per unit time. The activity is directly determined by the quantity of radioactive material in a sample, and is generally a much more convenient quantity to use than the number of radioactive atoms. The traditional unit for activity is called the curie (Ci).

1 curie = 3.7 x 10^{10} disintegrations per second (dps)

OR

1 curie = 2.22 x 10^{12} disintegrations per minute (dpm)

Because the curie is a very large quantity, fractions of the curie are often used:

1 millicurie = (mCi) = 2.22 x 10^{9} dpm = 10^{-3} curies

1 microcurie = (μCi) = 2.22 x 10^{6} dpm = 10^{-6} curies

1 nanocurie = (nCi) = 2.22 x 10^{3} dpm = 10^{-9} curies

1 picocurie = (pCi) = 2.22 dpm = 10^{-12} curies

Since radioactive material is measured in units of activity, the decay equation now takes the form:

$$A = A_o e^{-\lambda t}$$

Where: A = Activity after some time t

A_O = Original activity of the sample

λ = The radioactive decay constant equal to $\frac{0.693}{T_{1/2}}$

t = Decay time

The half-life equation (section V) can be also used for activity, simply by replacing the number of atoms N and N_0 with the activities A and A_0.

It should be mentioned that the International System (SI) of units has defined the becquerel (Bq) as the unit of activity, equal to 1 disintegration per second. Thus:

1 Ci = 3.7×10^{10} Bq.

The becquerel is already in use in most parts of the world and in most modern scientific literature. The curie is still in common use in the United States, although it is expected that the becquerel will eventually replace the curie.

Specific activity refers to the amount of radioactivity per given mass or other similar units of the sample. Specific activity is usually expressed in terms of the disintegration rate (dps or dpm), or count rate (counts/min, cpm, or counts/sec, cps), or curies (or mCi, μCi) of the specific radionuclide per unit mass of the element. Therefore:

$$\text{SA} = \lambda N = \lambda \frac{6.02 \times 10^{23}}{m} Bq/g$$

where SA = specific activity, λ = decay constant, $N = \text{number of atoms} = \frac{6.02 \times 10^{23}}{m}$,

and m = molecular mass (grams/mole). Note that the units in this case are Bq/g (dps/g).

VII. INTERACTIONS OF RADIATION WITH MATTER

Radiation interacting with matter can be either scattered or absorbed. The mechanisms of the absorption of radiation are of interest because: a) absorption in the body tissues may result in biological injury; b) absorption is the principle upon which detection of radiation is based; c) the degree of absorption is the primary factor in determining proper shielding requirements.

The transfer of energy from emitted radiations to matter occurs in two major ways: ionization and excitation.

Ionization: The process resulting in the removal of an electron from an atom, leaving the atom with a net positive charge.

Excitation: Addition of energy to an atomic system, transferring it from the ground state to an excited state. No ion pair is formed, but energy is then given off by the atom as fluorescent radiation or low energy x-rays when the atom returns to its ground state.

Radiation can be classified into two groups:

1) Particulate radiation such as alpha and beta particles
2) Electromagnetic radiation such as x-rays or gamma rays.

Particulate radiation can be either charged (alpha or beta particles) or uncharged (neutrons); however, only charged particle interactions will be discussed here.

A. Interactions of Charged Particles

All atoms are normally electrically neutral. When a charged particle strikes an orbital electron it ejects it from the atom, resulting in the formation of an ion pair. Since the removal of the electron from the atom decreases the total number of negative charges by one, it leaves the atom with a net positive charge. The ion pair consists of:

1) The positively charged atom
2) The negatively charged electron

Such particles capable of creating ion pairs in this manner are called ionizing radiation.

The term used to compare and relate the ionizing powers of different types of charged particles is specific ionization. Specific ionization is defined as the number of ion pairs per unit path length formed by ionizing radiation in a medium:

$$\textit{Specific ionization} = \frac{\#\textit{ of ion pairs formed}}{\textit{path length (cm)}}$$

The specific ionization is dependent on the velocity and mass of the charged particle (and therefore its energy), the charge of the particle, and the density of the absorbing material (the number of atoms available for ionization).

The most common types of charged particles encountered in most applications are alpha particles and beta particles. Their particular interactions are described in more detail below.

1. <u>Alpha Particles</u>

An alpha particle is a helium nucleus stripped of its orbital electrons. It is emitted from a radioactive atom with a velocity of about 1/20 that of the speed of light and with energies ranging from 4 to 9 MeV. Alphas cause ionizations in matter when they are deflected by the positive charge of a nucleus and pull the orbital electrons (attracted by the alpha's positive charge) along with them. Alpha particles also cause excitation along their path by pulling inner orbital electrons to outer orbits. Energy is then given off by the atom as fluorescent radiation (low energy x-rays) when the electrons drop back down to the inner orbital vacancies.

Because of its relatively large mass (2 neutrons and 2 protons), high electrical charge (2+) and low velocity, the specific ionization of an alpha particle is very high. That is, it creates many ion pairs in a very short path length. Because of this, it loses all of its energy in a very short distance. The range in air is only several centimeters even for the most energetic alpha particles.

Since the alpha particle has a very limited range in matter, it presents no external radiation hazard to man. Many alpha particles cannot penetrate the protective layer of skin. However, once inside the body, surrounded by living tissue, damage will be to the local area in which the alpha emitter is deposited. Thus, alpha emitters are an internal hazard and intake to the body must be prevented.

2. <u>Beta Particles</u>

Beta particles are emitted from the nucleus of a radioactive atom with a wide range of energies up to some maximum value. When a beta is emitted that is below the maximum value, the neutrino carries away the rest of the energy.

Beta particles, like alpha particles, lose their energy by ionization and excitation, but because of their small mass (1/7300 of an alpha) and lower charge (1/2 of that of an alpha) the interactions take place at less frequent intervals. Therefore, the beta particles do not produce as many ion pairs per centimeter of path as alpha particles, and thus, have a greater range in matter. The beta particle's range in matter depends on its energy and the composition of the material.

a) Bremsstrahlung X-ray Production:
Beta particles can interact with the nucleus of an atom and give rise to x-rays by a method called <u>Bremsstrahlung</u>. Bremsstrahlung (German for "Braking Radiation") occurs when a high-speed beta

particle approaches the nucleus of an atom. The electrical interaction between the negative beta particle and the positively charged nucleus causes the beta particle to be deflected from its original path or stopped altogether. This stoppage or deflection results in a change in velocity, or deceleration, of the beta particle with the emission of x-rays of various energies. The likelihood of Bremsstrahlung production increases with increasing atomic number of the absorber. For this reason, beta shields are made from low atomic number materials, like aluminum or plastics, to reduce Bremsstrahlung production. X-ray tubes are made with high atomic number materials, to encourage Bremsstrahlung production.

Beta particles require an energy of greater than 70 keV to penetrate the protective layer of the skin, and thus, are somewhat of an external hazard. The beta can also constitute an internal hazard. A beta particle has a greater range in tissue compared to an alpha particle due to its low specific ionization, therefore, it gives up less energy per unit volume of tissue and is not as effective in causing damage as an alpha particle.

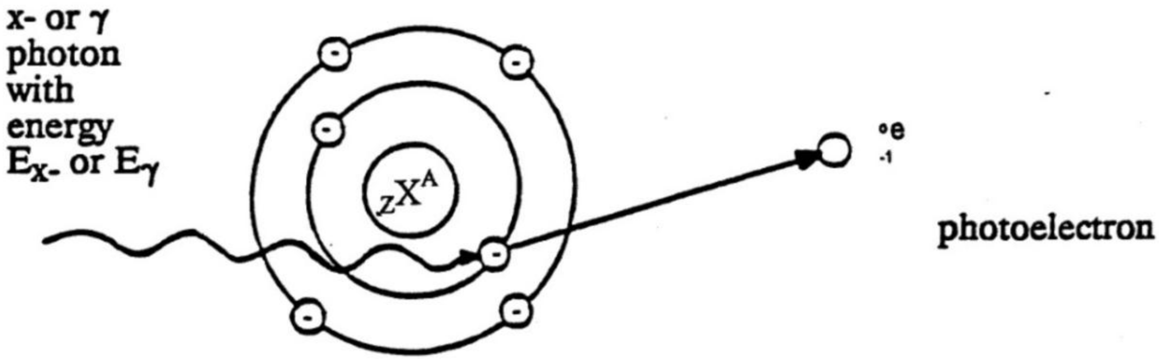
B. Interaction of X-Rays and Gamma Rays

From a practical radiation protection point of view, x-rays and gamma rays are identical, differing only in their place of origin. Gamma rays are emitted with discrete energies from excited nuclei. X-rays are emitted from outside the nucleus; i.e., an outer shell electron replaces a missing lower shell electron and a characteristic x-ray is produced, or the interaction of beta particles causes Bremsstrahlung radiation to be produced. The energy of a characteristic x-ray is approximately equal to the difference in the electron energy levels, but Bremsstrahlung radiation produces a continuous spectrum of energies up to some maximum value.

Since x- and γ rays are chargeless, they do not interact by electrostatic forces as in the case of charged particles, which cause ionization of matter directly along their path of travel. However, x- and gamma rays do have sufficient energy to release secondary charged particles (electrons) from matter through one of three basic interactions: the Photoelectric Effect, the Compton Effect, and Pair Production. The high-speed electrons resulting from these interactions then cause ionization of the medium.

1. <u>The Photoelectric Effect</u>

The Photoelectric Effect is the interaction of x- or γ-ray photons as well as other photons (such as light), whereby all of the energy of the photon is transferred to an inner shell electron (usually the K shell), ejecting it from the atom and leaving the atom with an inner shell vacancy. This shell vacancy creates an excitation energy which corresponds to the binding energy (BE) of the ejected photoelectron.



The kinetic energy (KE) of the photoelectron is equal to the energy of the x- or γ-ray photon minus the BE of the electron ejected:

$KE_{photoelectron} = E_{X-}$ or E_γ - BE of electron

If the x- or γ photon does not have sufficient energy to knock the inner shell electron loose, the reaction will not occur.

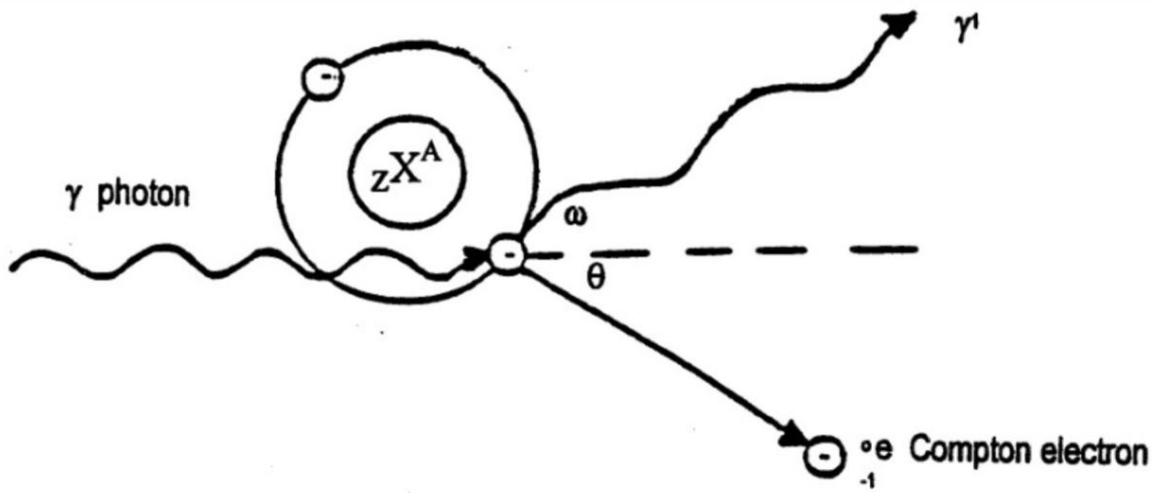
The resultant atom is now in an excited state and will decay to the ground state by emission of x-rays and fluorescent radiation. The energies of the secondary radiations are usually much lower than the primary x- or γ-ray energies.

Application of the Photoelectric Effect

Gamma rays emitted from excited nuclei, and x-rays emitted from excited atoms, have discrete energy characteristics of the specific nuclides and elements, respectively. Thus, the energy of these γ or x- photons can be used as "finger prints" to identify nuclides and elements. The photoelectric effect is also the means by which photons are absorbed by shielding materials and radiation detectors.

2. The Compton Effect (named after A. H. Compton)

Photons with energies much greater than the BE of the electrons in an atom may interact through scattering interactions in which the total KE of the system is conserved. In this interaction, the electron appears to the photon as a free electron (BE = 0).



The primary γ loses part of its energy to the Compton electron which gets scattered at an angle Θ from the original direction of the incident γ, while the Compton scattered γ (γ') is scattered at an angle ω (see diagram). In this process the scattered photon and Compton electron share the energy of the incident photon (γ).

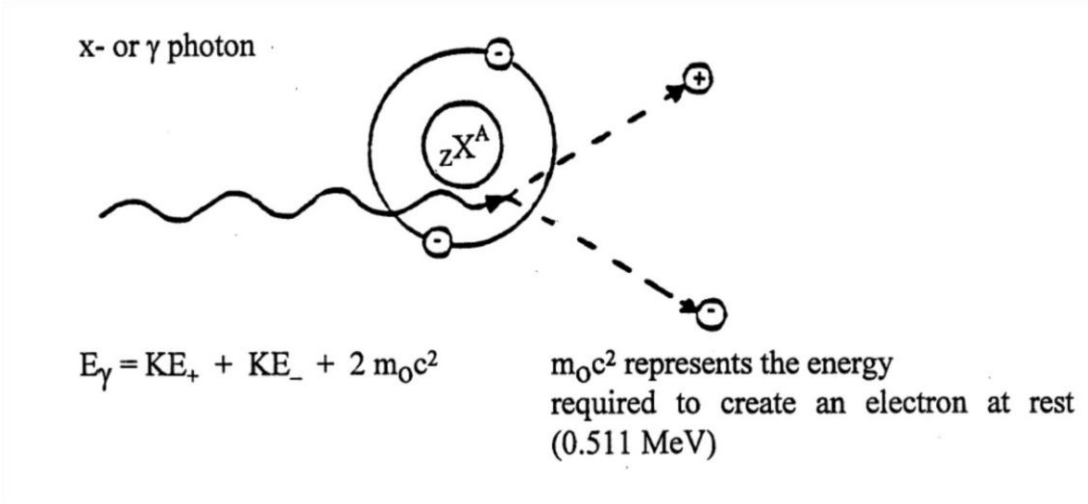
The KE carried off by the Compton electron may be deposited locally (i.e., absorbed immediately by the surroundings). However, the energy carried off by the Compton scattered photon is not deposited locally. Therefore, this scattered photon can significantly contribute to the dose outside a shielding apparatus.

Application of the Compton Effect

Due to its characteristic peaks, the Compton effect aids in the identification of unknown nuclides. However, in a detecting system, the Compton scattered electron can mask lower energy photons interacting by the photoelectric effect, making interpretation of results difficult.

3. Pair Production

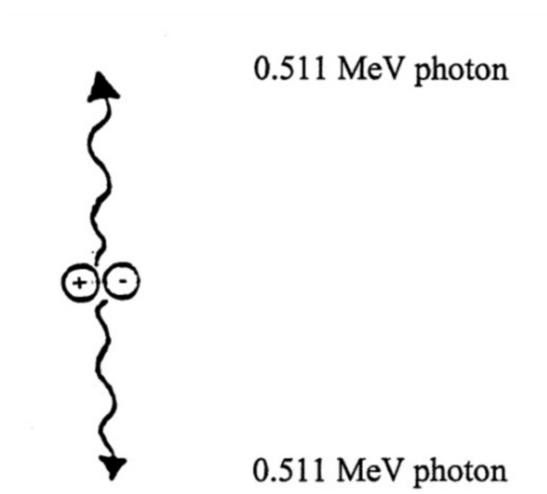
High-energy gamma photons transfer their energy primarily by pair production. A high-energy x- or γ-ray passing close to a nucleus suddenly disappears and an electron and a positron appear in its place. This interaction must take place in an electric field, usually that of the nucleus, in order to conserve momentum.



Since both particles are created from energy supplied by the incident photon, the process is energetically possible only if E_γ is greater than 1.022 MeV, which is the sum of the rest mass energy of an electron and a positron (0.511 MeV each). "Rest mass energy" is the amount of energy that would be released if a particle of mass *m* is converted to energy, which is possible according to Einstein's famous theory that $E = mc^2$, where:

E = photon energy (in joules – can be converted to MeV)
m = rest mass of two electrons (in kilograms)
c = the velocity of light (3×10^8 m/sec)

When the positron slows down (i.e., loses its KE), it will undergo positron annihilation by combining with an electron. This produces two photons with energies of 0.511 MeV each, emitted 180^o apart from each other. This "annihilation radiation" represents the rest mass energy of two electrons, which is converted to pure energy in the form of photons.



Applications of Pair Production

Again, due to characteristic peaks observed for various known nuclides, Pair Production is an aid in the identification of unknowns.

VIII. RADIATION QUANTITIES AND UNITS

Radiation can be measured in different ways depending on the amount, energy, and type of radiation. Additionally, the quantity reported depends on what is of interest – some quantities are true measurements, but others are calculated quantities that refer to the effect radiation has on matter or biological tissue. In everyday use, the distinctions between measured and calculated quantities are often blurred, but it is important to understand the different quantities and units that are used when referring to radiation.

It is also important to understand that units have changed over time. Traditional units are still used by regulatory agencies in the United States, but most of the world and most scientific literature now use SI units. Both are presented here. The constants applicable to some calculated quantities have also been changed over time as research provides more accurate numbers; however, U.S. regulatory agencies still use the older numbers, so multiple sets are presented when necessary.

A. Count Rate

The most basic measurement is the count rate, which is the number of radiation interactions that occur in a detector in a certain period of time. This measurement is reported in units such as cps (counts per second) or cpm (counts per minute). It is most useful for measuring particulate radiation, although it can be used for small quantities of x-ray or gamma radiation.

It is common to see count rate reported in dps (disintegrations per second) or dpm (disintegrations per minute), although this is not actually a true count rate. Measurements reported in dps or dpm have had the efficiency of the detectors taken into account in order to estimate the true disintegration rate (see Chapter 4 for more information).

B. Exposure

Exposure is a measurement of the amount of electric charge produced by photons in a mass of air. The electric charge comes from the production of ion pairs, which are collected by the detector and measured as a current. It can be measured as a rate (exposure per unit time), for sources which emit radiation continuously, or as a total integrated exposure, for sources such as x-ray tubes that emit radiation in a single pulse.

The traditional unit used for exposure is the roentgen (R). 1 R is the amount of radiation required to liberate one electrostatic unit of charge (of either sign) in 1 cm^3 of air at standard temperature and pressure (STP). This amounts to roughly 2.08 x 10^9 ion pairs. In SI units, 1 R = 2.58×10^{-4} C/kg.

C. Absorbed Dose

Absorbed dose is a measure of the energy deposited in a material by all types of radiation. The traditional unit is the rad (radiation absorbed dose), which is equal to 100 ergs/gram. The SI unit for absorbed dose is the gray (Gy), equal to 1 joule/kg. 1 Gy = 100 rads.

Absorbed dose is difficult to measure directly, and so is frequently calculated from other quantities such as exposure. In order to calculate it, it is necessary to know the correct conversion factor for the material of interest. For example, to convert exposure to dose in air, $D_{air}\,(\text{rad}) = 0.88\,(\text{rad/R}) \times X\,(\text{R})$, where D = absorbed dose and X = exposure. However, to convert exposure to dose in tissue, $D_{tissue}\,(\text{rad}) = 0.93\,(\text{rad/R}) \times X\,(\text{R})$.

Note- In radiation protection, the roentgen and rad are often used interchangeably since, in tissue, they are approximately equal. Strictly speaking, though, the roentgen is a unit of exposure and applies only to x- or gamma radiations.

D. Equivalent Dose / Dose Equivalent

Equivalent dose (H_T) is a quantity calculated from the absorbed dose that takes into account that some types of radiation are more harmful to biological tissue than others. It is equal to the absorbed dose in a tissue from each type of radiation ($D_{R,T}$) multiplied by a radiation weighting factor (w_R) for that type of radiation, summed over all types of radiation present:

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

The traditional unit used for dose equivalent is the rem, which stands for "roentgen equivalent man". The SI unit is the sievert (Sv), and 1 Sv = 100 rem. The radiation weighting factor is unitless; however, a different unit is used for the equivalent dose to make it easily distinguishable from the absorbed dose.

Note that, prior to 1990, "equivalent dose" was referred to as "dose equivalent", and the quality factor (Q) was used instead of the radiation weighting factor. (U.S. regulatory agencies still use this convention.) H_T is calculated in the same way for both quantities, although some values for Q differ from the current values for w_R. See the table below for a list of these constants.

Radiation Type	Quality Factor	Radiation Weighting Factor
x-rays, γ rays, or β particles	1	1
Neutrons (depends on energy)	2-11	5-20
Protons (high-energy)	10	2-5
Alpha particles	20	20

Example: What is an individual's equivalent dose from 10 mR of gamma rays, 5 mrad of β particles and 10 mrad of alpha particles? (m = milli = 1/1000). Assume 1 R = 1 rad.

Dose Equivalent	= mrad	x	w_R	= mrem
Gamma dose equivalent	= 10	x	1	= 10
Beta dose equivalent	= 5	x	1	= 5
Alpha dose equivalent	= 10	x	20	= 200
		TOTAL		= 215 mrem

E. Effective Dose / Effective Dose Equivalent

The ED or EDE is a quantity that takes into account that the various organs and tissues of the human body respond to radiation differently. It is used primarily in radiation protection, and is intended to compare the risk of stochastic effects associated with a non-uniform exposure to radiation with that of a uniform whole-body exposure. A stochastic effect is a health effect that occurs randomly and for which the probability of the effect occurring, rather than its severity, is assumed to be a linear function of dose (example: getting cancer). The ED is intended to estimate risk for radiation protection purposes only, and is not intended for calculating individual-specific doses.

The ED is calculated by multiplying the equivalent dose (H_T) to each organ/tissue by the tissue weighting factor for that organ/tissue (w_T), summed over all the organs/tissues in the body:

$$E = \sum_T w_T \times H_T$$

The unit for the ED remains the rem or sievert. The ED was formerly called the EDE and was denoted H_E instead of E, but both quantities are calculated in the same manner. The primary difference is that the tissue weighting factors changed between the two quantities – the ED uses weighting factors published in 1990, whereas the EDE uses weighting factors published in 1977. There is also a newer set of 2007 recommendations, although they have not yet been officially published (see the table below).

Tissue or Organ	w_T (2007 recomm.)	w_T (ICRP 60 - 1990)	w_T (ICRP 23 - 1977)
Gonads	0.08	0.20	0.25
Bone marrow	0.12	0.12	0.12
Colon	0.12	0.12	N/A
Lung	0.12	0.12	0.12
Stomach	0.12	0.12	N/A
Bladder	0.04	0.05	N/A
Breast	0.12	0.05	0.15
Liver	0.04	0.05	N/A
Esophagus	0.04	0.05	N/A
Thyroid	0.04	0.05	0.03
Skin	0.01	0.01	N/A
Brain	0.01	N/A	N/A
Salivary glands	0.01	N/A	N/A
Bone surface	0.01	0.01	0.03
Remainder	0.12	0.05	0.30

The tissue weighting factor is an estimate of the proportion of the risk of stochastic effects resulting from irradiation of an organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly. Thus, a higher number corresponds to a higher risk.

F. Committed Effective Dose / Committed Effective Dose Equivalent

The CED or CEDE is a quantity that calculates the total dose an individual would receive over a lifetime from an intake of radioactive material. It is equal to the ED or EDE (corresponding to the CED or CEDE, respectively) integrated over a period of 50 years following the intake for adults, or to age 70 for children. Note that the dose rate usually decreases over time, depending on the half-life of the substance and the speed at which it is eliminated from the body.

G. Total Effective Dose / Total Effective Dose Equivalent

The TED or TEDE is simply equal to the sum of the radiation dose from external radiation plus the dose from internal radiation. Thus:

$$\text{TED} = \text{ED} + \text{CED} \quad \text{or} \quad \text{TEDE} = \text{EDE} + \text{CEDE}$$

IX. CONVERSION OF TRADITIONAL UNITS TO S.I. UNITS

QUANTITY	TRADITIONAL UNIT	S.I. UNIT
ACTIVITY	CURIE (Ci)	BECQUEREL (Bq)
EXPOSURE	ROENTGEN (R)	COULOMB/KILOGRAM (C/kg)
ABSORBED DOSE	RAD	GRAY (Gy)
EQUIVALENT DOSE	REM	SIEVERT (Sv)

CONVERSION FACTORS FROM TRADITIONAL UNITS TO S.I. UNITS:

1 curie = 3.7 x 10^{10} disintegrations/sec
1 microcurie = 2.22 x 10^{6} disintegrations/min
1 disintegration/second = 1 becquerel (Bq)
1 curie = 3.7 x 10^{10} becquerel (Bq)
1 millicurie = 37 megabecquerel
1 nanocurie = 37 Bq
1 roentgen = 2.58 x 10^{-4} coulomb/kilogram
100 rads = 1 gray (Gy)
100 rems = 1 sievert (Sv)

X. SOURCES OF INFORMATION ON RADIONUCLIDES

There are several sources of information providing useful summaries of the properties of radionuclides. One is the Chart of the Nuclides, available from Knolls Atomic Power Laboratory, Lockheed Martin, 1310 Kemper Meadow Drive, Cincinnati, OH, 45240 (http://www.chartofthenuclides.com). Every stable or radioactive nuclide is assigned a square on the diagram. Isotopes occupy horizontal rows and isotopes occupy vertical columns. Isobars fall among descending 45° lines. Basic properties of each nuclide are listed in the boxes, including atomic number, neutron number, atomic weight, thermal neutron capture cross section, half-life, and other data. The Chart of the Nuclides also diagrams the transformations that occur for various decay modes and is particularly useful for tracing through a radioactive series.

A most useful source of data for radionuclides of interest is a shareware software program entitled RADDECAY, available from the UF Radiation Control and Radiological Services Department. RADDECAY is a program for displaying radioactive decay information for 497 radionuclides. Data provided include the half-life, radioactive daughter nuclides, probabilities per decay, and decay product energies for alphas, betas, positrons, electrons, x-rays, and gammas.