Understanding Radiation Science:
Basic Nuclear and Health Physics

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CHAPTER I

Introduction

The purpose of this book, *Understanding Radiation Science: Basic Nuclear and Health Physics*, is to provide the reader a basic understanding of radiation science. Therefore, basic nuclear physics and health physics principles are presented, including chapters on atomic structure, types of radiation, terminology and units, radiation biology, exposure and controls, background radiation, and personnel monitoring.

Radiation is the energy emitted from an atom in the form of particles or electromagnetic waves. Radiation (ionizing radiation), as used in this book, means alpha particles, beta particles, gamma rays, x-rays, and neutrons. These radiations will be defined later. It does not include non-ionizing radiation, such as radio waves, microwaves, or visible, infrared, or ultraviolet light.

Physics deals with understanding and explaining the behavior of matter and energy and the fundamental forces of nature that govern the interactions between particles
In comparison, chemistry deals with the rearrangements of the atoms that form molecules and the analysis and synthesis of materials.

Nuclear physics is the branch of physics concerned with the nucleus of the atom. It is usually applied to nuclear energy and nuclear power. Whereas, atomic physics or atom physics is physics of the electron hull of atoms. Physicists distinguish between atomic physics (dealing with the effects of the electron hull and the nucleus's overall spin and electric charge) and nuclear physics (dealing with the forces within the atomic nuclei and reactions that alter, fuse or split them).
Biophysics or biological physics is an interdisciplinary science that applies theories and methods of the physical sciences to questions of biology. Nuclear engineering is the practical application of the principles of nuclear physics and the interaction between radiation and matter.

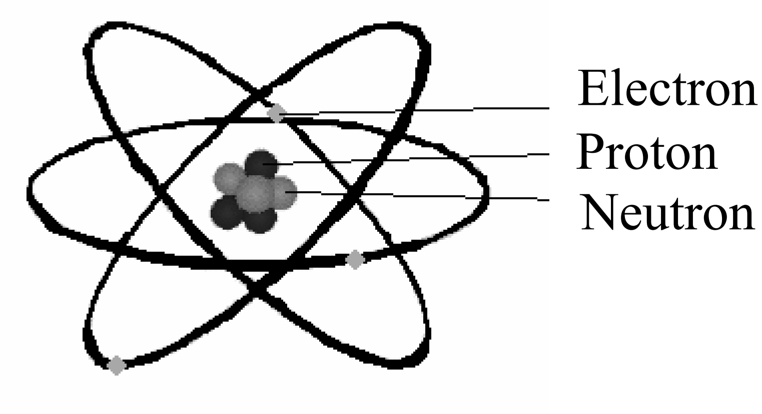
Health physics is the profession devoted to the protection of man and his environment from unwarranted radiation exposure. *Exposure* means being exposed to ionizing radiation or to radioactive material. Therefore, a health physicist is a person engaged in the study of the problems and practice of providing radiation protection. He is concerned with an understanding of the mechanisms of radiation damage, with the development and implementation of methods and procedures necessary to evaluate radiation hazards, and with providing protection to man and his environment from unwarranted radiation exposure. Health physics encompasses many disciplines, including physics, biology, chemistry, and ecology.

Atomic Structure

Matter is composed of chemical elements such as oxygen, hydrogen, carbon or iron. The smallest piece that an element can be broken into and still retain its identity is called an atom. It is the fundamental building block of elements. Atoms of all elements are made of three basic particles. The proton carries one positive charge of electricity. The electron carries one negative charge of electricity. The neutron is electrically neutral or has no charge of electricity.

The protons and the neutrons form the densely packed nucleus of the atom around which revolves electrons. The electron is the smallest of the primary particles. It orbits around the atom's nucleus and is held in orbit by the attraction of the negative charge of the electron and the positive charge of the nucleus. The proton is about 1840 times larger than the electron. It is the positive charge of the proton that gives the nucleus of the atom an overall positive charge. The neutron is a neutral particle. Scientists believe that the neutron is composed of a proton and an electron. Since the charges will cancel each other out, the result is a neutral particle.

The nucleus of the atom is the mass in the center, around which the electrons rotate. Both the neutron and the proton are in the nucleus of the atom. The charge of the nucleus is electrically positive. The number of protons in the nucleus determines the strength of the net positive charge and the name of the element. For example, if the nucleus of an atom contained one proton, the element would be hydrogen. If another proton could be added to the nucleus, the element would be helium. Neutrons exist in the nucleus in different numbers, but have no effect on the element or its chemical properties.



The atom is neutral, because it has the same number of electrons as protons. The number of protons or electrons of an atom is its atomic number, Z. This determines what chemical element the atom is. For example, hydrogen has an atomic number of one and helium has an atomic number of two. All atoms of the same element have the same number of protons in the nucleus, but they can have different numbers of neutrons and still be atoms of the same element. If the nucleus of an element has more neutrons in it than another nucleus of the same element, that atom with more neutrons in its nucleus will be heavier. The number of neutrons in the nucleus is denoted by *N*. The total number of protons and neutrons in the nucleus is the atomic weight or atomic mass of an atom. The atomic mass of the nucleus, *A, is* equal to *Z* + *N*.

$${}^{\textbf{Atomic mass (A)}}_{\textbf{Atomic number (Z)}}\textbf{Element} = {}^{239}_{94}\textbf{Pu}$$

The term ^{239}Pu means the atom of plutonium with an atomic weight of 239. Since the atomic number of plutonium is 94, it has 94 protons in the nucleus. 239-94=145. So there are 145 neutrons in the nucleus of ^{239}Pu. Since the number of neutrons has no effect on the atomic number or the chemical properties of the atom, an atom with one proton is hydrogen whether it has one, two or three neutrons. Atoms of the same chemical element having different numbers of neutrons are called isotopes of the element. All isotopes of an element have the same atomic number but different atomic weights.

An atom normally has the same number of orbiting electrons as it has protons in the nucleus. Every element has a different number of electrons orbiting around the nucleus. It is the number of electrons and their orbit that determines the chemical properties of the element.

Some elements have an excess of either protons or neutrons in their nucleus. These elements are unstable. These unstable elements seek stability by emitting either particles of matter or electromagnetic energy. In radiating or emitting this excess energy as ionizing radiation, the atoms become a different element or a lower energy (more stable) form of the original element

CHAPTER II

Types of Radiation

The nucleus of an atom is normally stable, but some atoms have unstable nuclei. These unstable nuclei are called radioactive atoms. They are at an excited or highly energetic state. When the atom drops from an unstable state to a stable state, energy is given off. This energy is radiation and may be in the form of electromagnetic energy or the ejection of particles from the nucleus. This radiation may be gamma, x-ray, beta, alpha or neutron radiation.

Ernest Rutherford discovered that uranium compounds produce three different kinds of radiation in 1899. He named them α. alpha, β beta, and γ gamma radiation. He separated the radiations according to their penetrating abilities with alpha being the least penetrating, gamma being the most penetration, and beta falling between.

X-rays are penetrating electromagnetic radiations whose wave lengths are shorter than visible light. X-rays are produced by bombarding a metallic target with fast electrons in a vacuum. As orbital electrons fall from a higher to lower energy orbital shell, energy is released in the form of electromagnetic radiation.

Gamma rays are short wavelength electromagnetic radiations emitted from the nucleus of an atom. Gamma rays are the same as x-rays except they originate in the nucleus of the atom instead of the electron cloud. It is customary to refer to electromagnetic energy originating in the nucleus as gamma rays, and those originating in the electron shell as x-rays. All electromagnetic radiations travel at the velocity of light, which is about 3×10^8 meters per second (m/s). The gamma ray is a highly penetrating type of nuclear radiation. Gamma rays or photons do not consist of particles, have no mass, travel at the speed of light, and do not lose their energy as rapidly as either alpha or beta particles. Gammas produce no direct ionization by collision as alpha and beta particles, because gamma photons have no mass. They are absorbed or lose their energy by three processes known as the photoelectric effect, the Compton effect, and pair production.

Beta particle is emitted from the nucleus of an atom, with a mass and charge equal in magnitude to those of the electron. In other words, a beta particle is an electron that originates in the nucleus of an atom. A neutron consists of a proton and an electron that combined to form electrically neutral particle. When a neutron decays in the nucleus, it may eject the electron. This high speed electron is a beta particle. The neutron in the nucleus becomes just a proton, and the atom's atomic number increases by one. The atom weight of the atom remains the same. Beta particles are less penetrating than gamma rays or x-rays, but more than alpha particles. The beta particle does not lose its energy as rapidly as the alpha particle. This is because the beta particle a very small particle, has less charge than the alpha particle, and is moving at a higher rate of speed. The range of velocities for beta particles ranges from about 25 to 95 percent of the speed of light. The range of the beta particle is approximately inversely proportional to the density of the material through which it passes. Beta particle has little penetrating power. It has a range in air from less than an inch to several feet. It can be stopped by a board of inch or by a 1/8 inch of aluminum.

*Alpha particl*e consists of two protons and two neutrons ejected from the unstable nucleus. This particle has a net charge of plus two. The alpha particle is equal in charge and mass to the nucleus of a helium atom. Since the alpha particle consists of two neutrons, the emission of an alpha particle will decrease the atomic weight by four and will decrease the atomic number by two. Alpha particles are comparatively large, heavy particles of matter which have been ejected from the nucleus of a radioactive material with a very high velocity. Alpha particles lose their energy rapidly and hence have a limited range. They travel only about 6 or 7 centimeters in air. The alpha particle is the least penetrating of the three common forms of radiation, being stopped by a sheet of paper. It is not dangerous to living things unless the alpha-emitting substance is inhaled or ingested or comes into contact with the lens of the eye. Then they are very harmful.

When an alpha or beta particle is emitted, the atomic number changes because the chemical properties of an atom are determined by that atom's atomic number. The ejection of a particle (alpha or beta) and/or energy (gamma rays) from the nucleus is call disintegration.

Neutron radiation is usually caused by some outside force affecting the nucleus. The nuclei of an atom may be bombarded by an alpha or beta particle causing the emission of a neutron. One of the most important methods of neutron radiation production is fission. Fission is the splitting of a nucleus into two or more other nuclei and the release of a relatively large amount of energy. In addition to the fission-product nuclei, some individual neutrons are also released. So when fission occurs, fission products are created, and neutrons and energy are released. For all practical purposes, only a small number of "heavy" atomic nuclei are fissionable. The best-known fissionable atoms are ^{235}U and ^{239}Pu. Spontaneous fission is when a nucleus undergoes fission without outside help. This is also a source of neutrons and energy. Neutrons and energy are also produced by fusion. This is when two light atomic nuclei are joined together to form a single heavier nucleus. Neutron radiation is very penetrating. This radiation is readily shielded by about a foot of material that contains a large percentage of hydrogen atoms, such as water or polyethylene. Neutron radiation at very high energies has the ability to make other materials radioactive if they absorb neutrons.

CHAPTER III

Terminology and Units

The properties of radiation and radioactivity are measured in certain units. There are several units of radiation quantity. It is impossible to measure a quantity of radiation directly, since it can bring about a change in matter only to the extent of the energy that is absorbed by this matter.

Dose measurement terminology and definitions are important to understand and use properly. Radioactivity has its own specific terminology and definitions, as well. The different terms that are used with dose and its measurement and radioactivity and its measurement are presented below.

One must understand and use these terms precisely to convey the proper meaning in the radiation sciences. This is very important. Serious mistakes can result from improper use of terminology. Most of the following definitions come from regulatory sources.

Dose Measurements

Dose or *radiation dose* is a generic term that means absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent, committed effective dose equivalent, or total effective dose equivalent, as defined in other paragraphs of this chapter.

Occupational dose means the dose received by an individual in the course of employment in which the individual's assigned duties involve exposure to radiation or to radioactive material. Occupational dose does not include doses received from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive material in voluntary participation in medical research programs, or as a member of the public. *Public dose* means the dose received by a member of the public from exposure to radiation or to radioactive material released by a licensee, or to any other source of radiation under the control of a licensee. Public dose does not include occupational dose or doses received from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive material in voluntary participation in medical research programs.

External dose means that portion of the dose equivalent received from radiation sources outside the body, and i*nternal* dose means that portion of the dose equivalent received from radioactive material taken into the body. *Absorbed dose* means the energy imparted by ionizing radiation per unit mass of irradiated material. The units of absorbed dose are the rad and the gray (Gy).

The *roentgen* (R) is a unit for measuring gamma rays or x-rays only. This unit measures x-ray or gamma radiation in terms of the charge deposited in one unit volume of air. One roentgen equals 2.58 x 10-4 coulomb per kilogram of air.

The *rad*, radiation absorbed dose, is a quantity of any type of ionizing radiation in terms of the energy absorbed per unit mass of material. The rad is the unit of absorbed dose equal to 0.01 Joules per kilogram in any medium.

The *gray* (Gy) is the International System of Units (SI) unit used to measure a quantity called absorbed dose. One gray is equivalent to an absorbed dose of 1 Joule/kilogram or 100 rad. Absorbed dose is often expressed in terms of hundredths of a gray, or centigrays (cGy).

Dose equivalent (H_T) means the product of the absorbed dose in tissue, quality factor, and all other necessary modifying factors at the location of interest. The units of dose equivalent are the rem and sievert (Sv).

Since roentgen measures radiation in air only, it cannot be used to measure to biological effects on man. One reason is radiation acts differently in air and tissue. The *rem*, roentgen equilavent man, is used to measure the biological effects of radiation. It is a special unit of dose equivalent. The dose equivalent in rems in numerically equal to the absorbed dose in rads multiplied by the quality factor (QF), the distribution factor, and any other necessary modifying factors.

The *Sievert* (Sv) is the International System of Units (SI) unit used to derive a quantity called equivalent dose. Equivalent dose is often expressed in terms of millionths of a Sievert, or microsievert (mSv). To determine equivalent dose (Sv), you multiply absorbed dose (Gy) by a quality factor (QF) that is unique to the of incident radiation. One Sievert is equivalent to 100 rem.

The *quality factor* (QF) is the linear-energy transfer-dependent factor by which the absorbed dose (rad) is multiplied to obtain a quantity that expresses the effectiveness of the absorbed dose on a common scale for all ionizing radiations. For most beta or gamma radiation, the QF is 1. So 1 rad is equal to 1 rem. The rem is actually defined as the amount of any type of ionizing radiation which produces the same biological effect as 1 rad of gamma radiation. An R is also about equal to 1 rad or 1 rem for gamma radiation.

Since the R, the rad, and the rem are rather large quantities of radiation, they may be subdivided into smaller units. The "m" is an abbreviation for “milli-“, a prefix that means one-thousandth of.one milliroentgen (mR), millirad (mrad) and millirem (mrem) are one-thousandths of these radiations. The units of radiation measurement discussed above are used to express the dose. The dose is a quantity of radiation received by material. The rate at which the radiation is received is called the dose rate. So dose will be written as mR, mrad, or mrem. The dose rate will be expressed as mR/hr., mrad/hr.or mrem/hr.

The *collective dose* is the sum of the individual doses received in a given period of time by a specified population from exposure to a specified source of radiation. The *committed dose equivalent* ($H_{T,50}$) means the dose equivalent to organs or tissues of reference (T) that will be received from an intake of radioactive material by an individual during the 50-year period following the intake. The *committed effective dose equivalent* ($H_{E,50}$) is the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues ($H_{E,50} = \Sigma W_T H_{T.50}$). The e*ffective dose equivalent* (H_E) is the sum of the products of the dose equivalent to the organ or tissue (H_T) and the weighting factors (W_T) applicable to each of the body organs or tissues that are irradiated ($H_E = \Sigma W_T H_T$).

Total Effective Dose Equivalent (TEDE) means the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures). *Shallow-dose equivalent* (Hs), which applies to the external exposure of the skin of the whole body or the skin of an extremity, is taken as the dose equivalent at a tissue depth of 0.007 centimeter (7 mg/cm^2).

The w*eighting factor* W_T, for an organ or tissue (T) is the proportion of the risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly.

Radioactivity

The *Becquerel* (Bq) is the International System of Units (SI) unit used to measure radioactivity. One Becquerel is that quantity of a radioactive material that will have 1 transformation in one second (1 dps or 1 d/s), also written one Becquerel=1 disintegration per second (s^{-1}). There are 3.7 x 10^{10} Bq in one Curie. Radioactivity is often expressed in larger units like: thousands (kBq), millions (MBq) or even billions (GBq) of a Becquerel.

The *curie*, Ci, is a measure of radiation activity on how fast the radioactive substance is giving off radiation. One curie of any radioactive material is the amount of the material in which 3.7 x 10^{10} atoms disintegrate per second (dps or d/s). Each disintegration of an atom is really the emission of radiation by its unstable nucleus. If one has some radioactive material like plutonium and it produces 3.7 x 10^{10} alpha particles each second, then one has one curie of plutonium. Therefore, one curie=$3.7\text{x}10^{10}$ disintegrations per second=$3.7\text{x}10^{10}$ becquerels=$2.22\text{x}10^{12}$ disintegrations per minute. Since a curie is a large amount of radiation, the terms millicurie (mCi) and microcurie (µCi) are often used. A millicurie (mCi) is one thousanth of a curie (3.7 x 10^{7}