CHAPTER 1

Radiation

Radiation should be considered a double-edged sword. This is because radiation can kill, as demonstrated by the outcome of the dropping of atomic bombs at Hiroshima and Nagasaki in Japan and the disastrous incidents at nuclear reactor plants around the world, most recently at Chernobyl, Ukraine in April 1986. On the other hand, radiation can cure, as applied extensively in the diagnosis and treatment of diseases since the discovery of x-rays and radioactivity. The word "Gamma knife" was coined by a neurosurgeon for a machine using gamma radiation as a knife to surgically remove lesions in the brain. We know that radiation plays an integral role in the practice of modern medicine. For those of us who are interested in the medical use of radiation, radiation should be understood and respected as a potent tool. The outcome of this respect is the safe and proper use of radiation to derive the maximum benefit to mankind. In this first chapter, we shall introduce the medical use of radiation and then proceed with examining the nature and different types of radiation. Next, radiological quantities and units shall be presented. We shall also examine the sources, ionizing effects, and safe handling of radiation and sources. Lastly, a historical perspective of radiological physics and its branches shall be dealt with in this chapter.

1.1 Medical Use of Radiation

Radiation is effectively used in **radiological imaging**, a noninvasive procedure that provides both visual and quantitative assessments of many internal anatomical structures and functional changes in a human body. Imaging procedures that are available in radiology and nuclear medicine departments include static x-ray radiographs, fluoroscopy, angiography, computed tomography (CT), positron emission tomography (PET), magnetic resonance imaging (MRI), ultrasound imaging, single photon emission computed tomography (SPECT), and radionuclide imaging. Each of these imaging procedures reveals different aspects of tissue composition or functions of the human body. Generally, ultrasound imaging and MRI imaging are preferred because these techniques do not use ionizing radiation. Besides imaging, radiation is used to treat lesions in radiation therapy. The use of radiation alone or in combination with surgery and/or **chemotherapy**, is now the standard of practice for treating cancers. Other treatment modalities are hyperthermia and phototherapy. **Hyperthermia** uses heat generated from microwaves and ultrasound to treat superficial and deep-seated lesions, respectively. **Phototherapy**, which uses visible light to treat superficial lesion, is still in an experimental stage. Lasers of frequencies in the range of visible light are now routinely used in surgery. Infrared radiation (IR) has been used in **thermography** to map blood flow or heat distribution in a body, for example, before and after smoking. However, the use of this technique has declined.

Both static and dynamic x-ray radiographs use frequencies in the range of 10^{17}–10^{19} Hz. A static x-ray radiograph is taken by exposing a patient to an x-ray source. Because the patient absorbs radiation differentially, the transmitted radiation forms a latent image of the patient, which can be captured using a detection system or film. Dynamic x-ray radiographs as used in angiographic studies, provide functional information of the human anatomy. Contrast or radio-opaque material injected in an angiographic procedure can be used to visualize any obstruction within the blood circulatory system. Computed tomography, which provides cross-sectional anatomical information, is constructed by detecting a series of radiation intensities around a patient and then performing back projection reconstruction using computer software.

Radionuclide imaging relies on the detection of gamma (γ) rays with frequencies greater than 10^{18} Hz emitted from bio-distribution of radioisotopes. Radioisotopes in the form of gases or liquids are administered to patients to perform physiological studies in nuclear medicine. Differential uptake of radioisotopes within the body depends on the type of markers, affinity of the organs, and the circulatory system. Once these radioisotopes have reached the desired location, the emitted radiation is detected using gamma detectors called **gamma cameras**. These detected gamma rays infer the absorption of the markers by the body tissues leading to the interpretation of functional information about the pathways and/or obstructions in the circulatory systems. The gamma camera gives only two-dimensional data while the SPECT system provides three-dimensional data giving the nuclear medicine physician additional information to make a proper diagnosis. The SPECT system has 1 to 3 gamma cameras to collect gamma rays around the patient. After the gamma rays are collected, they are back-projected to generate three-dimensional images, which can be viewed in the axial, coronal and sagittal planes. The PET system also provides three-dimensional information, like the SPECT system, except that gamma rays come from positron annihilation.

Radioactive materials are also used in the laboratory to perform "in-vitro" or test-tube studies on blood, urine, or cells. For example, radioactive tritiated thymidine (^{3}H TdR) has been used to study the radiosensitivity of the cell cycles.

Magnetic resonance imaging (MRI) produces images based on the difference in the magnetic response of protons. The relaxation of these protons in their environment after excitation creates different magnetic decay strengths, which are processed to show different tissue types. Magnets of strength in the range of 0.5 – 1.5 Tesla (kilogauss) are commonly used to provide an external uniform magnetic field with higher fields up to 8 Tesla for experimental work. For comparison, the Earth's magnetic strength is about 0.5 gauss. In addition to being subjected to the large static uniform magnetic field, the patient undergoing the imaging procedure is also exposed to changing magnetic field gradients and radiofrequencies used to localize and induce a signal. Radiofrequency waves (also called RF waves or radiowaves) are used to excite magnetic dipole moment of protons in tissues. The de-excitation processes emit signals, which are detected and Fourier transformed, and then processed to form images in three dimensions. MRI generally reveals the water content and chemical composition of tissues. Although the health effects due to these magnetic fields on patients and personnel are considered small, physical injuries caused by fast moving magnetic objects brought near the magnetic fields have been reported.

Ionizing radiation is routinely used to treat both benign and malignant diseases. Benign diseases include arterial-venous malformation (AVM), acoustic neuroma, heterotopic bone growth, and keloid. Recently, an interest has been recognized in the use of radiation from brachytherapy sources to inhibit the occlusion of arterial vessels in endovascular therapy (also called **intravascular brachytherapy**). In addition to benign and malignant tumors, radiation is also used as an immuno-suppressor in bone marrow transplant.

The mode of radiation delivery or treatment depends on whether the radiation source is far away or close to the patient. If the source is far away from the patient, the treatment is referred to as **teletherapy** or **external beam therapy**. If the source is near or within the patient, the treatment is referred to as **brachytherapy** (brachy means short in Greek). In brachytherapy, the radioactive sources are usually encapsulated and sealed into small pellets to minimize the risk of source contamination. If the radioactive sources are left in the body for only a few days, the implant is called a **temporary implant**. These implants are typically identified as low dose rate (**LDR**) implants using low activity sources. Another type of temporary implants is the high dose rate (**HDR**) implants where the sources are left in the patients for only a few minutes and immediately removed after treatment. If the radioactive sources are left in the patient permanently, the implant is called a **permanent implant**. Unsealed or liquid sources used for radiation treatment are referred to as **internally administered radionuclides**. Iodine-131 (^{131}I) taken orally is used for the treatment of thyroid cancers. Strontium-89 (^{89}Sr) and samarium-153 (^{153}Sm) administered intravenously have been used for bone pain palliation.

A **laser** (an acronym for **l**ight **a**mplification by the **s**timulated **e**mission of **r**adiation) is a device that emits a coherent narrow intense beam of a single frequency. It has found many applications that include the use as a surgical tool for removing tissues, cauterizing wound to halt bleeding, and breaking up gallstones and kidney stones. Dermatologists use lasers to treat skin conditions such as wrinkles, spider veins, birthmarks, and warts. The treatment is permanent with less risk of scarring compared to other techniques such as chemical peel and dermabrasion. Different types of lasers are available depending on the wavelength of light used. The laser types and their light emission characteristics are given in Table 1.1. Because a laser produces intense beam, it is imperative that lasers must be rigidly held before being activated to avoid unnecessary exposure to patient as well as personnel. Eye protection should be worn and access to the lasers should be controlled.

Table 1.1 Different types of lasers

Lasers	Light emission
Flash scan CO_2 gas	infrared
Continuous CO_2 gas	infrared
Flash lamp pulse dye	yellow
Argon gas	blue-green
Neodymium-YAG: yttrium - aluminum-garnet	infrared
Ruby	red

Ultrasound imaging has become a popular modality for the diagnosis of diseases, as well as defining anatomical structures. It uses sound waves with frequencies in the range of 1 – 10 MHz, which is higher than the sound barrier (hearing range $20 - 20 \times 10^3$ Hz) and hence cannot be detected by our hearing sense. Ultrasound waves are **longitudinal waves**, a form of mechanical waves. This is different from electromagnetic waves because sound waves require a medium of propagation and carry no electromagnetic properties. In addition, the displacement of the molecules is in the direction of propagation. Whenever there is a medium density interface, the ultrasound waves are partially transmitted and partially reflected back to the source. The time required for the reflected wave to reach the transmitter is directly related to the depth of the interface. The reflected ultrasound waves from many interfaces form an anatomical image. Ultrasonic imaging is often used in fetal studies because the procedure does not involve ionizing radiation.

1.2 Nature of Radiation

Radiation refers to the propagation of energy through space or a medium. Radiation is odorless, tasteless, and invisible. Because of these physical properties, its effects are not physically observable. Radiation possesses both wave and particle properties. The wave nature of radiation was established based on the interference and diffraction of light experiments performed by an Englishman, Thomas Young (1773–1829) in 1801. Albert Einstein (1879–1955) predicted the particle nature of radiation in 1905. The results of two notable experiments, the photoelectric effect experiment carried out by Robert A. Millikan (1868–1953) in 1913 and the Compton effect named after its discoverer, Arthur H. Compton (1892–1962) in 1923, were explained using the particle nature of radiation. From these experiments, light is said to possess the wave-particle duality property. Light is part of the electromagnetic radiation. Based on this unusual property of light and the concept of symmetry in nature, Prince Louis Victor de Broglie (1892–1987) in 1923 proposed that matter might have wave properties. This wave nature of particles was confirmed by the experiment of Clinton J. Davisson (1881–1958) and Lester H. Germer (1896–1971) in early 1927, showing that electrons incident onto the surfaces of metal crystals are scattered in pattern of regular peaks as a function of scattering angle. To clarify this concept of wave-particle duality for radiation, the famous Danish physicist named Niels Bohr (1885–1962) proposed the **principle of complementarity**. This principle states that either the wave model or the particle model may be used to understand an experiment but not both.

Radiation can be broadly classified as either **particulate** or **electromagnetic**. If the radiant energy is carried off by a particle that has rest mass, the radiation is called **corpuscular radiation** or particulate radiation. Particulate radiation can be further subdivided into charged particles and non-charged particles. Examples of charged particles are alpha particles, protons and beta particles. Non-charged particles are neutrons. **Electromagnetic (EM) radiation** is a packet of energy called a photon that propagates through space. Examples of EM radiation are x-rays and gamma rays.

The interaction of radiation with matter will probably cause excitation and ionization of the atoms. As will be explained in later chapters, **excitation** refers to the process where energy is absorbed causing an electron to jump to a higher energy orbit in an atom. On the other hand, **ionization** refers to the process where energy is absorbed to cause the ejection of an electron from an atom. Of the two interacting processes, ionization is disruptive to the atoms changing the molecular integrity that leads to cell death in tissues. Radiation has been classified as ionizing and non-ionizing. If the interaction of the radiation does not cause ionization, the radiation is called **non-ionizing radiation**. Non-ionizing radiation includes all electromagnetic radiation like microwaves and radiowaves except x-rays and gamma rays. The classification of radiation is summarized in Table 1.2. Ionizing radiation can be further subdivided into **directly ionizing** and **indirectly ionizing** radiation. In directly ionizing radiation, the energy deposited comes directly from Coulomb interaction as it traverses through the medium causing disruption to the atomic structure of the absorber and thereby creating chemical and biological damages. Examples of directly ionizing radiation are charged particles such as alpha particles, beta particles, and protons. In the case of indirectly ionizing radiation, the radiation does not produce any chemical or biological damage but transfers its energy to the absorber to create fast-moving charged particles. The energy deposited by the fast-moving secondary charged particles produces the disruption and biological damage. Examples of indirect ionizing radiation are any uncharged particles like neutrons, x-rays, and gamma rays. If the energy is sufficiently high, the interaction may cause nuclear disintegration.

Table 1.2 Classification of radiation types

Radiation Types		
Ionizing		Non-ionizing
Directly	Indirectly	
α particles	x-rays	All electromagnetic radiation except x-rays and γ rays
β particles	γ rays	
Protons	Neutrons	

1.3 Quantum Nature of Radiation

The concept of corpuscular radiation was proposed by Isaac Newton (1642–1727) and later modified by Max Planck (1858–1947). Max Planck postulated that light is a form of electromagnetic radiation having a discrete amount or quantum of radiant energy. This discrete quantum or packet of energy is called a **photon**. This discrete energy, E is related to its frequency denoted by the Greek letter, ν, (pronounced as "nu") as

$$E = h\nu \tag{1.1}$$

where h is Planck's constant having a value of 6.626×10^{-34} joule·second (J·s).

EXERCISE 1.1 Show that Planck's constant in the cgs system is 6.626×10^{-27} erg·sec. One joule is equal to 1×10^{7} erg.

The unit of frequency is the hertz (Hz), which is equal to one cycle per second. The frequency is related to its wavelength, denoted by the Greek letter, λ, (pronounced as "lambda") by

$$c = \lambda\nu \tag{1.2}$$

where c = 3×10^{8} meters per second (m/s) is the speed of light in vacuum. Inherently, equation (1.2) states that electromagnetic radiation travels at the speed of light in vacuum.

EXAMPLE 1.1 Compute the frequency of a photon whose wavelength is 1×10^{-10} m.
SOLUTION:
From equation (1.2),

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^{8}\ \text{m/s}}{1 \times 10^{-10}\ \text{m}} = 3 \times 10^{18}\ \text{Hz}$$

EXERCISE 1.2 Show that the speed of light is approximately 186,000 miles per second.

Equations (1.1) and (1.2) can be combined to relate the energy of the photon to its wavelength as

$$E = \frac{hc}{\lambda} \tag{1.3}$$

This equation states that photon energy increases with decreasing wavelength. Since h and c are merely constants, students performing EXERCISE 1.3 should be able to reduce this equation to

$$E\,(\text{keV}) = \frac{12.4}{\lambda\,(\text{Å})} \tag{1.4}$$

where E is expressed in keV and λ in units of angstrom (Å). One angstrom is equal to 1×10^{-10} m.

EXERCISE 1.3 Derive equation (1.4) by substituting the values of h and c into equation (1.3).

The unit of keV represents 1000 electron volts. One electron volt (eV) represents the amount of energy required to accelerate an electron through a potential of 1 volt. **One electron volt is equal to 1.602×10^{-19} joule**. The prefix k represents 1000. Some of the commonly used prefixes of unit are given in Table 1.3. Additional prefixes are given in Appendix B.

Table 1.3 Prefixes of units

Factor	Prefix	Symbol
10^{+9}	giga	G
10^{+6}	mega	M
10^{+3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n

Associated with the use of the prefix notation is the scientific notation. Scientific notation is a mathematical expression using a number between 1 and less than 10, plus an exponent to the power of 10 to represent a decimal number. A decimal number written in scientific notation has the form of

$$A \times 10^{n} \tag{1.5}$$

where $1 \le A < 10$ and n is an integer. The major advantages of scientific notation are its compactness and the unambiguous way of indicating the degree of accuracy of the decimal number by the number of significant figures.

EXAMPLE 1.2 Compute the wavelength of a 1 MeV photon and express the value in scientific notation.
SOLUTION:

The relationship between energy and wavelength is given by equation (1.4) as

$$\lambda = \frac{12.4}{E} = \frac{12.4}{1 \times 10^{3}\,(\text{keV})} = 1.24 \times 10^{-2}\ \text{Å} = 1.24 \times 10^{-12}\ \text{m}$$

In addition to the quantized nature, a photon also carries oscillating electric and magnetic fields that are orthogonal to each other and to the direction of propagation. **A photon possesses no rest mass and carries no charge**. It possesses a spin of 1, and its momentum p can be expressed as

$$p = \frac{E}{c} \tag{1.6}$$

where E is the photon energy and c is the speed of light. The electromagnetic radiation can also be polarized in the direction of the angular momentum. **Photons also exhibit both wave-like and particle-like behaviors**. Light diffraction pattern is explained by assuming light to be waves, while photoelectric effect is explained by assuming light to be particles as discussed in Section 1.2.

The idea of wave-particle duality for photons was extended to matter by Louis de Broglie. He postulated that if light waves possess particle-like characteristics, then particles could also possess wave-like characteristics. The postulation of the wave aspect of matter called **de Broglie wave** or **matter wave** makes it possible to explain the quantization of angular momentum postulated by Niels Bohr. The de Broglie wavelength associated with a particle moving at a velocity, v is given by

$$\lambda = \frac{h}{m\,v} = \frac{h}{p} \tag{1.7}$$

where h is Planck's constant, $p = mv$ is the momentum, and m is the mass of the particle. The validity of equation (1.7) was confirmed by the Compton effect experiment. C.J. Davisson and L.H. Germer confirmed the duality nature of matter, as proposed by de Broglie at Bell Laboratory in their electron diffraction experiment in 1927. They used electrons to probe the surface of a sample of nickel crystals and observed unexpected peaks in their results. This peak was due to the diffraction from crystals. When these peaks were interpreted as diffraction pattern, the wavelength of the diffracted electron was found to be that predicted by Louis de Broglie. Later experiments showed that protons, neutrons, and other particles also exhibit wave properties.

According to the special theory of relativity proposed by Albert Einstein, the mass of a particle is given as

$$m = \frac{m_o}{(1-\beta^2)^{1/2}} \tag{1.8}$$

where

$$\beta = \frac{v}{c}$$

v is the velocity of the mass, m_o is the rest mass, and c is the speed of light. **Relativistic mass** refers to the increase in mass at high velocities, which is predicted by equation (1.8). At a low velocity, β is very small and hence the denominator has a value almost equal to one. The mass of the particle is principally its rest mass. As the velocity increases, the denominator, $1-\beta^2$ becomes smaller and the mass becomes larger. As the velocity approaches the speed of light, the denominator approaches zero and therefore the mass becomes infinite which is not possible. This implies that matter cannot travel at the speed of light.

EXAMPLE 1.3 Show that if the speed of an electron is 86.6% of c, it will yield a relativistic mass equal to twice the rest mass.
SOLUTION:

Substitute the speed into equation (1.8),

$$m = \frac{m_o}{\sqrt{1-\beta^2}} = \frac{m_o}{\sqrt{1-(v/c)^2}} = \frac{m_o}{\sqrt{1-(0.866)^2}} = \frac{m_o}{\sqrt{0.25}} = 2m_o$$

The total energy of a particle is given as

$$E = m\,c^2 \tag{1.9}$$

which is the Einstein equation (also called mass-energy equivalence equation). For a stationary particle, the energy equivalent rest mass is determined by initially calculating the rest mass through setting $v = 0$ in equation (1.8). The rest mass is converted into energy using equation (1.9) to arrive at

$$E_o = m_o c^2 \tag{1.10}$$

Now, we define the kinetic energy as the difference between the total energy and its energy equivalent rest mass, as

$$KE = m\,c^2 - m_o c^2 \tag{1.11}$$

At very low velocity, equation (1.11) can be simplified by first performing binomial expansion to the denominator of equation (1.8). Next, we note that $v << c$, which allows us to drop the third and higher order terms leading to

$$KE = \tfrac{1}{2} m\,v^2 \tag{1.12}$$

Equation (1.12) describes the kinetic energy of a particle.

EXERCISE 1.4 Derive equation (1.12) by performing binomial expansion on equation (1.11) and allowing β to approach zero.

In terms of relativistic momentum, equation (1.9) can be represented as

$$E^2 = p^2 c^2 + m_o^2 c^4 \tag{1.13}$$

where $p = mv$ is the momentum of the particle.

EXERCISE 1.5 Derive equation (1.13) by solving equation (1.9) for E^2.

1.4 Electromagnetic Radiation Spectrum

Electromagnetic radiation is emitted from the oscillations of electric charges. The source of oscillating electric charges can be from radio antenna or from electrons revolving around a nucleus. **Electromagnetic (EM) waves are composed of oscillating electric and magnetic fields that are orthogonal to each other and to the direction of propagation** as shown in Figure 1.1. To reiterate, **EM waves propagate at the speed of light, c**. The square of the amplitude of the field strengths is proportional to the energy propagated.

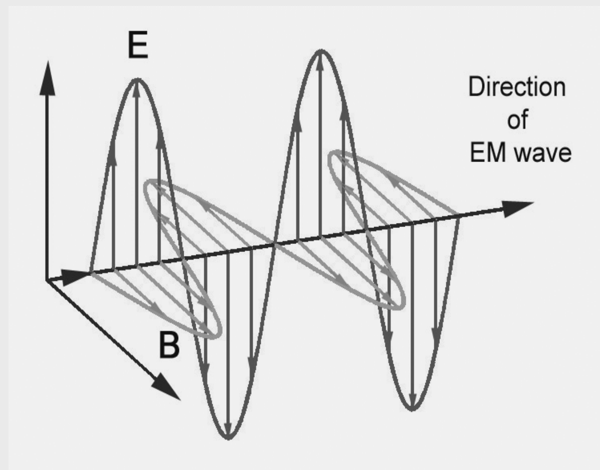

Figure 1.1 Propagation of EM waves [provided by Sicong Li, DSc]

Propagation of energy in the form of waves is well understood through the contributions of James Clerk Maxwell (1831–1879). Using the four basic equations that describe all electric and magnetic phenomena, James Maxwell predicted that accelerating electric charges produce transverse EM waves and these waves propagate through space at the speed of light. These four equations involving electric and magnetic fields are known as Maxwell's equations. **Maxwell's equations are the fundamental equations for electromagnetism**. James Maxwell also made the argument that light must be an EM wave based on the calculation of the speed of these waves. The idea was not fully accepted until Heinrich Hertz demonstrated the existence of EM waves. Later, EM waves were shown to travel at the speed of light and exhibit the characteristics of light such as reflection, refraction, and interference. Light, which is visible to our human eyes, is a part of the EM waves.

The spectra of electromagnetic waves are broad and continuous from radiowaves to x-rays with wavelengths from 10^6 to 10^{-13} cm. The electromagnetic wave spectra with their corresponding wavelength, frequency, and energy are shown in Figure 1.2. The wavelength and energy are related by equation (1.1) and equation (1.2). Alternating electric currents (ac) in wires carrying electric power generate long wavelengths. Next to the electric power are the radiowaves used for transmission in radio, television, microwaves, and radar. Among the radiowaves, radar uses the shortest wavelength. This wavelength is comparable to the wavelength of sound. Radiowaves and infrared waves have long wavelengths or low frequencies. Heated solids and the molecular vibrations and rotations in gases and liquids produce infrared radiation. Infrared radiation is mainly responsible for the heating effects from the sun and often is referred to as **space heating**. The sun emits not only visible light but also substantial infrared and ultraviolet radiation, all contributing to the production of solar energy for our use.

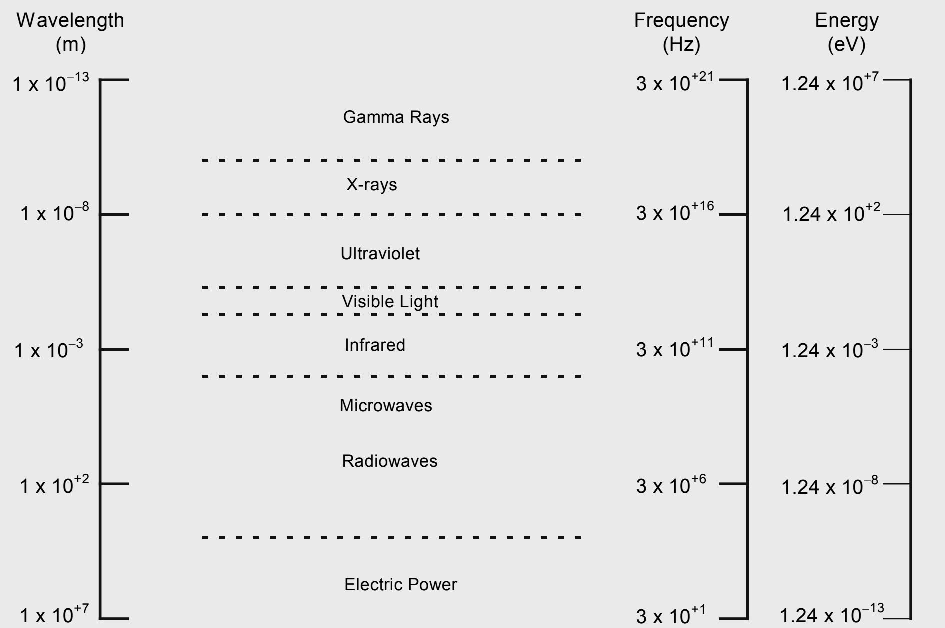

Figure 1.2 Electromagnetic wave spectrum

Our skin resonates at infrared frequencies, causing energy absorption that warms our bodies. Our eyes are sensitive to visible light, having a very narrow range of wavelengths from 4000 Å (violet) to 7000 Å (red). Radiation with wavelengths shorter than visible light is ultraviolet light followed by x-rays and gamma rays. X-rays and gamma rays are at the high-energy end of the EM spectrum and completely overlap each other. As such, an x-ray and a gamma ray are indistinguishable except for their origins, which will be discussed in Section 1.8.

EXERCISE 1.6 Compute the wavelength of a 1 keV x-ray and compare it to the size of an atom ($\approx 10^{-10}$m).

An x-ray or a gamma ray with energy greater than 100 eV is classified as ionizing radiation. The radiation is characterized by its ability to produce ionization in matter and to penetrate into substances.

In summary, radiowaves have the longest wavelengths and the lowest frequencies, while **x-rays and gamma rays have the shortest wavelengths and the highest frequencies**. Radiation with wavelength shorter than that of visible light is classified as ultraviolet rays, x-rays, and gamma rays. The boundaries between these adjoining regions are not sharply defined. They are only distinguishable by their methods of production. Ultraviolet rays are produced from light sources, x-rays from electric generators and atomic transitions and gamma rays from radioisotopes. The various types of EM radiation interact differently with the same materials. For example, materials that are opaque to visible light can be transparent to x-rays.

There are many applications of EM waves. The human eye is sensitive only to visible light allowing us to see things in this world. Because of the electromagnetic properties, EM waves permit the electronic transmission and receiving of information over long distances. Radiowaves are electromagnetic signals emitted from radio or television stations and received by our radios and televisions in our homes. AM radio stations broadcast at the carrier frequencies from 530–1700 kHz while FM frequencies range from 88–108 MHz. The carrier frequencies for TV stations are from 54–216 MHz for **VHF (very high frequencies)** stations for channels 2 through 13 and from 470–890 MHz for **UHF (ultra high frequencies)** stations for the higher channels. Cellular phones operate in the range above the TV broadcast frequencies. Radar used for detecting objects at distance uses frequencies in the microwave range. Computer data transmitted through wireless network operates in the range of 902 MHz to 928 MHz and from 2.4 GHz to 2.484 GHz.

1.5 Particulate Radiation

A distinct difference between electromagnetic radiation and particulate radiation is that **particulate radiation carries a rest mass**. An example of particulate radiation is the electron. The electron has a rest mass (m_e) of 9.109×10^{-31} kg and one unit negative (–1e) charge. **One unit of electrical charge is equal to 1.602×10^{-19} coulomb (C)**. Every atom contains electrons orbiting around its nucleus. Since an electron possesses a unit negative charge, it is easily detected. Beams of high-energy electrons are extensively used in radiation therapy. Some examples of particulate radiation and their physical properties are given in Table 1.4. The commonly encountered types of particulate radiation in radiological medicine are electrons, beta particles, protons, neutrons, and alpha particles. Of lesser importance are heavier nuclei like mesons and carbon ions.

Table 1.4 Types of particle radiation

Particle	Mass	Charge
electron	m_e	–1e
positron	m_e	+1e
negatron	m_e	–1e
proton	1836 m_e	+1e
neutron	1839 m_e	0
alpha particle	4 u	+2e
mu meson	207 m_e	–1e, +1e
pi meson	273 m_e	–1e, +1e
heavy charged particle		

m_e is the mass, e is the charge of an electron, and u is the atomic mass unit ($1u = 1.6605 \times 10^{-27}$ kg)

Beta (β) particles, also called beta rays, are emitted during nuclear disintegration. The beta particle possesses a mass identical to that of an electron, however the charge can be either negative or positive. If the beta particle has a unit negative (–1e) charge, the beta particle is called a **negatron** (or beta–minus particle), denoted by the symbol, β^-. Since there is no difference between a negatron and an electron, a negatron is often referred to as an electron and designated as ${}^{0}_{-1}e$. The only difference between a negatron and an electron is its origin. Unstable nuclei with excess neutrons tend to disintegrate by emitting negatron to gain nuclear stability. A negatron comes from a nucleus while an electron comes from the atomic shell. In nuclear disintegration involving the emission of beta particles, there is also the emission of either a **neutrino** or an **anti-neutrino**. These particles have no charge, are practically without any rest mass and travel at almost the speed of light. For the above reasons, neutrinos and anti-neutrinos are difficult to detect. If the beta particle has a unit positive (+1e) charge, the beta particle is called a **positron** (or beta–plus particle) denoted by the symbol, β^+or ${}^{0}_{+1}e$. Unstable neutron deficient nuclei usually disintegrate by emitting positron to gain nuclear stability. Once emitted, the positron will slow down and comes to rest. It will immediately annihilate by combining with an electron to produce two photons whose energies are 0.511 MeV and travel in opposite directions to each other. The simultaneous detection of these two photons is the basis of positron emission tomography (PET) imaging.

Protons and neutrons are basic constituents of a nucleus. A proton is basically a stripped hydrogen atom without its orbiting electron. It has one unit positive charge with a mass approximately 1836 times the mass of an electron. Protons and neutrons are not emitted during nuclear decay because much higher energy is needed to overcome their binding energies compared to the binding energies of alpha particles or beta particles. Instead, alpha particles and beta particles are the preferred particles of emission during a nuclear decay. Beams of proton are used in radiation therapy.

EXERCISE 1.7 Using the mass in Appendix C, show that the mass of a proton is about 1836 times heavier than the mass of an electron. Also show that the mass of a neutron is about 1838.5 times heavier than the mass of an electron. A generalization can be made that both protons and neutrons are about 2,000 times heavier than electrons.

A neutron has a rest mass slightly greater than that of a proton but carries no charge. Since a neutron has no charge, it is very difficult to stop and cannot be detected directly. A neutron exists in free state for only a very short time and disintegrates into a proton, an electron, and an antineutrino. If the neutron does not disintegrate, the neutron enters an atomic nucleus with ease since there is no inhibiting Coulomb barrier. Neutrons are broadly classified according to their kinetic energies as **thermal or slow moving neutrons** (0 – 0.1 keV), **intermediate neutrons**, and **fast neutrons** (20 keV – 10 MeV). When higher than 10 MeV, they are called **high-energy neutrons**. Thermal neutrons have the same kinetic energy as molecules at ordinary temperature. They are easily captured by atomic nuclei forming a stable or radioactive nuclide. On the other hand, fast moving neutrons must be slowed down before they can participate in a nuclear reaction. The mechanism of energy transfer is through collisions with nuclei. Maximum energy transfer for a fast moving neutron occurs when the recoil nucleus has the same mass as the neutron. Light nuclei present the most efficient material for slowing down fast neutrons to thermal levels. Water and paraffin containing a higher percentage of hydrogen atoms are best suited for slowing down neutrons due to their inelastic scattering. The recoil nucleus, which carries charge, will subsequently ionize other atoms. Neutron beams have been used in radiation therapy.

An **alpha (α) particle**, also called alpha ray, is composed of two protons and two neutrons identical to a helium atom (^4He) without its electrons. The alpha particle possesses two units of positive (+2e) charge. Because of their large mass, alpha particles move slowly while ionizing and exciting atoms along their path. The alpha particle, when combined with two electrons, forms a neutral helium atom. Alpha particles are produced from natural radioactive decay of heavy nuclei with atomic number greater than 82 and nuclear reaction using particle accelerator.

The **mu (μ) meson** also called muon was discovered as a result of the search for a particle predicted by Yukawa's theory of nucleon binding. Yukawa's particle has an intermediate mass between an electron and a proton and hence is called a meson. However, the muon has smaller mass, longer half-life and incorrect spin compared to the particle predicted by Yukawa's theory. The Yukawa's particles are the "π" or pi mesons or simply pions. The pions decay into muons and neutrinos. The muons can posses either a unit positive or negative charge and have mass approximately 207 times that of an electron.[1] Muons are unstable and decay spontaneously into electrons and neutrinos. The mean life of these particles is about 2.15×10^{-6} seconds. Being charged particles and having large masses, muons have the potential to cause significant biological damage as they traverse through tissues.

1.6 Identification of Radiation Types

The types of radiation can be identified according to their charge property by allowing the radiation to pass through a perpendicular magnetic field as discovered by Rutherford. For gamma rays, which carry no charge, they are not influenced by the magnetic field and hence will pass through the magnetic field without deflection. Likewise neutrons, which carry no charge, can pass through the magnetic field without deflection. For alpha particles, which carry positive charges and negatrons, which carry a unit negative charge, are deflected in opposite directions when traversing through the magnetic field.

The types of radiation can also be identified according to their penetrability into matter. The magnitude of the penetrability can be estimated by allowing the radiation to traverse through different materials. Qualitatively, gamma rays have greater penetrating power requiring several feet of cement or inches of lead to stop it. On the other hand, beta particles do not ordinarily penetrate deep into the skin. As such, beta particles are used primarily for superficial radiation treatment. However, beta particles pose a significant hazard if they bypass the skin (via oral ingestion, inhalation, absorption, or injection) because of their ability to ionize tissues. The beta particles can be

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[1] Johns, H.E.; Cunningham, J.R. *The Physics of Radiology*. 4th ed. Springfield, IL: Charles C Thomas Publisher; 1983. pp. 16-17.

absorbed by either an inch of wood, one-quarter inch of plastic or several feet of air. Alpha particles are much less penetrating and hence can be stopped with 2 – 3 inches of air or a thin sheet of paper. Alpha particles cannot penetrate deep into tissue but stop within the outer layer of human skin. With the limited penetrability, alpha ray beams are not used for radiotherapy. However, alpha particles can cause lung tissue damage if inhaled. Such is the case when radon gas is trapped in a house without adequate ventilation and air circulation.

1.7 Radiological Quantities and Units

Like every physical science, the measurement of any radiological quantity is made relative to a particular standard or unit. The four radiological quantities are radiation exposure, absorbed dose, dose equivalent, and radioactivity. Their associated units are roentgen, rad, rem and curie, respectively. Table 1.5 presents these radiological units and their *Systeme International* (SI) equivalent units.

Table 1.5 Radiological quantities and units

Quantity	Unit	Values	SI Unit
Rad Exposure	R	2.58×10^{-4}	C/kg
Absorbed Dose	rad	1×10^{-2}	Gy
Dose Equiv	rem	1×10^{-2}	Sv
Radioactivity	Ci	$3.7 \times 10^{+10}$	Bq

Radiation exposure is a quantity that describes the amount of electrical charges of all ions of one sign produced from the ionization of a unit volume of air. The old unit of radiation exposure is the '**roentgen**', named after Wilhelm Roentgen who discovered x-rays in 1895. One roentgen (R) is equal to the amount of radiation that will produce 2.08×10^{9} ion pairs (1 esu of charge) within a cubic centimeter (cm^3) of air at standard temperature pressure condition (STP). In SI unit, 1 R is equal to 2.58×10^{-4} coulomb per kilogram (C/kg) of air.

EXAMPLE 1.4 Express the exposure of 17 R in coulomb per kilogram (C/kg).
SOLUTION:

$$X = 17\,\text{R} \times \frac{2.58 \times 10^{-4}\ \text{C/kg}}{\text{R}}$$
$$= 4.39 \times 10^{-3}\,\text{C/kg}$$

By definition, the concept of radiation exposure applies only to x-rays and gamma rays with energies less than 3 MeV, and is also restricted to ionization of air.

EXERCISE 1.8 Show that 2.08×10^{9} ion pairs per cm^3 of air (STP) are produced in one R.

Absorbed dose is a quantity that describes the amount of energy absorbed in a medium from all types of radiation. As defined, the absorbed dose does not differentiate between the types of medium and the types of radiation. It is dependent on the radiation quality or energy, exposure, and nature of the medium. The traditional unit of absorbed dose is the **rad** (acronym of **r**adiation **a**bsorbed **d**ose). This unit is usually used to quantitatively express the amount of radiation received by a patient in tissues. One rad is equal to 100 ergs of energy absorbed in a gram of matter, e.g., **1 rad = 100 erg/gm**. It has the unit of energy per unit mass. The gray (Gy) is a derived SI unit of absorbed dose. **One Gy is equal to 1 J/kg or 100 rads**. Conversely, 1 rad is equal to 1 cGy or 0.01 Gy. Since radiation measurement is typically carried out in air, the absorbed dose in air is an important concept in radiation dosimetry. The absorbed dose in air is obtained by multiplying the amount of ionization in air by W/e, which is the energy needed to create an ion pair. This W/e has a numerical value of 33.97 J/C for dry air.

EXERCISE 1.9 Show that 33.97 J/C is equivalent to 33.97 eV expended to produce an ion pair.

EXAMPLE 1.5 Show that the absorbed dose in air of 1 R is 0.876 cGy.
SOLUTION:

$$\begin{aligned} 1\text{R} &= (2.58 \text{ x } 10^{-4}\ \text{C} \cdot \text{kg}^{-1}) \text{ x } 33.97\ \text{J} \cdot \text{C}^{-1} \\ &= 8.76 \text{ x } 10^{-3}\ \text{Gy} \\ &= 0.876\ \text{cGy} \end{aligned}$$

The above calculation indicates that the numerical value expressed in R and cGy are different for the same amount of ionization. The **air kerma**, which is used to define absorbed dose in air, has a numerical value of 14% lower than the roentgen. Direct measurements of absorbed dose are difficult and impractical. Instead, radiation exposure is initially measured in air, and then the value is converted into absorbed dose using ratios of absorption coefficients, called f–factors.

The radiological unit of equivalent dose is the **rem** (acronym of **r**adiation **e**quivalent **m**an). This unit expresses the amount of biological damage produced when a particular type of radiation releases its energy and is absorbed by the tissues of a living object. It is used to quantify the radiation exposure received by personnel working in a radiation environment with multiple types of radiation, such as nuclear reactors or particle accelerators. The biological destructiveness is different for different types of radiation. The biological destructiveness of x-rays and electrons is assigned 1. Thermal neutrons are considered 5 times more destructive than x-rays. The SI unit of equivalent dose is the sievert (Sv) with absorbed dose expressed in Gy. **One sievert (Sv) is equal to 100 rem**. For radiation protection consideration in the medical field where the types of radiation used have the same biological destructiveness, the radiological quantities are often used interchangeably, i.e., $1 \text{ rem} \approx 1 \text{ rad} \approx 1 \text{ R}$ in spite of their known differences.

The phenomenon where radioactive materials disintegrate by emitting radiation to achieve nuclear stability is referred to as **radioactivity**. The amount of radioactivity is measured in units of **curie** (**Ci**), named after the French scientist, Madame Curie. A curie is equal to 3.7×10^{10} disintegrations per second (dps). A smaller unit of milliCurie (mCi) is routinely used in the field of radiological physics. The SI unit of radioactivity is the becquerel (Bq). It is equal to 1 dps typically denoted as the reciprocal of second (s^{-1}).

1.8 Sources of Radiation

X-rays are emitted from the rearrangement of inner electrons of an atom and hence is said to come from an **extra-nuclear source**. The rearrangement occurs because the atom wants to gain energy stability. The x-ray is emitted when an electron jumps from a higher energy-state to a lower energy-state. This type of x-ray is called **characteristic x-ray (or characteristic radiation)** because it uniquely characterizes the particular type of atom. Instead of emitting x-rays, the atom may eject one of its electrons. Such an electron is called an **Auger electron**. In general, the energy released from extra-nuclear radiation is typically less than that of intra-nuclear radiation.

Gamma rays are emitted when particles within the atomic nucleus rearrange themselves to gain energy stability. Thus gamma rays are said to originate from the **intra-nuclear source**. Whenever a nucleus undergoes restructuring, the nucleus is said to be radioactive. As a result of the restructuring, it emits gamma rays to remove excess energy. These gamma rays have energies that uniquely characterize the nucleus of a particular element. Instead of gamma rays, the nucleus may emit other forms of radiation like alpha particles, beta particles, a proton, or a neutron. The type of radiation emitted will depend on the energy available. In general, a combination of the various types of radiation may be emitted. During particulate emission, the nucleus is said to undergo **transmutation**, changing its nuclear species. For example, radium-226 is changed to radon-222 by emitting an alpha particle during nuclear decay. For heavy nuclides, nuclear fission is possible where the radiation emitted is in the form of large size nuclides, such as iodine-131 and cesium-137.

Another source of radiation arises from the deceleration of charged particles. This radiation, called **bremsstrahlung radiation** (also called white radiation or braking radiation) is emitted when a charged particle slows down near a nuclear field. The interaction causes the charged particle to change direction, slow down and release packets of electromagnetic energy as bremsstrahlung radiation. The bremsstrahlung radiation has an energy that is equal to the difference between the kinetic energies of the incident and scattered charged particle. The bremsstrahlung radiation exhibits a continuous energy spectrum implying that the charged particles are scattered with varying kinetic energies.

EXAMPLE 1.6 The incident electron has a kinetic energy of 50 keV. What is the energy of the bremsstrahlung radiation if the energy of the scattered electron is 10 keV?
SOLUTION:

$$E_x = E_{inc} - E_{sc} = 50 - 10 = 40 \text{ keV}$$

A positron at rest in its free state is short lived. It combines with an electron to produce two gamma rays traveling in directly opposite directions. During the annihilation process, the masses of the positron and electron are converted into energy. The radiation emitted is called **annihilation radiation**.

The source of radiation for medical use is from x-ray generating equipment and radioactive materials. X-rays are generated when high-energy electrons strike a target. As the electrons decelerate, bremsstrahlung radiation is generated in addition to characteristic radiation. In nuclear medicine procedures, the source of radiation is the result of the decay of the administered radioactive materials. In positron emission tomography (PET), which is used in brain studies, the radiation detected is the result of the annihilation of an electron and positron. As in diagnostic procedures, radiation used for radiation treatment is produced when electrons strike a target in a linear accelerator. The decay of radionuclides is the source of radiation for brachytherapy. It should be pointed out that we sometimes use the words, “radioactive sources” and “radiation sources” interchangeably. To be correct, radioactive sources are nuclides that undergo restructuring and are a subset of radiation sources. Radiation sources include sources of radiation outside the nucleus.

Besides x-rays and gamma rays, other types of radiation have also been used in therapeutic application as listed in Table 1.6. These particles are also found in cosmic rays.

Table 1.6 Various radiation types and sources

Radiation Types	Sources
β particles	radioactive decay, accelerator
α particles	radioactive decay, accelerator
protons	accelerator
neutrons	reactor, cyclotron, accelerator
π mesons	high energy accelerator

Electron beams with a number of energies are currently available from linear accelerators with dual photon beam energies. Cyclotrons, which are available at a few large medical centers and national laboratories produce neutron and proton beams for clinical use.

1.9 Effects of Ionizing Radiation

Of particular interest to radiological physics is the effect of ionizing radiation on matter. This is because of its important applications in medicine and its ability to cause biological damage. In radiation therapy, radiation is used for the treatment of cancers, while radiation from radionuclide is used to map the functional aspects of the human body in nuclear medicine. In diagnostic radiology, the attenuated radiation is reconstructed to produce anatomical images for the diagnosis of diseases.

Besides medical use, radiation has other practical applications. Radiation has been used for **carbon dating of rocks and fossils**. Radiation also has been employed in **killing microbes in food**. On December 2, 1997 the U.S. Food and Drug Administration approved the irradiation of meat to control meat-borne disease. This approval was accelerated with the recent outbreak of E.coli O157:H7 bacteria in beef patties from a Nebraska Foods Co. Irradiation has also been used to control trichina parasite in pork and insects in fruits, vegetables, and grains. Food products can be irradiated using the typical radioactive sources of cobalt-60 and cesium-137, electron beams or x-ray beams. To disinfect parasites and insects in meat, a dosage of around 1 kGy is used. Higher dosage around 1–10 kGy is used in food preservation. Even higher doses around 10–50 kGy are used for sterilization.[2]

The ionizing effects of radiation on matter are briefly identified as follows: (a) photographic effect, (b) luminescent effect, (c) ionizing effect, (d) thermoluminescent effect, (e) chemical effect, and (f) biological effect.

In **photographic effect**, the radiation interacts with silver halide crystals in the photographic emulsion. It reduces the silver halide to silver. When developed or processed, the latent image of the object is captured on film for visualization.

In **luminescence effect**, the radiation interacts with certain materials such as zinc cadmium sulfide, calcium tungstate, leaded barium sulfate, and rare earth phosphors (like lanthanum or gadolinium). The interactions cause these materials to glow in the dark.

In **ionizing effect**, the radiation ionizes gases and causes discharges in an instrument like the electroscope. The discharges are collected to create current for electronic measurements.

In **thermoluminescence effect**, the radiation interacts with certain crystals, causing electron excitation and thereafter electron trapping. When the crystal is heated, the trapped electron de-excites with the emission of light. This phenomenon is used in radiation protection as well as verification of dosimetry in radiation therapy.

In **chemical effect**, the color of certain dyes may change due to the effects of radiation.

In **biologic effect**, the exposure of cells to radiation can lead to cell death. In addition, there is the risk of radiation damage to the genetic material of many types of human cells. The biological effect occurs first at the chemical and biochemical levels, whereby molecular structures are disrupted causing the molecules to dysfunction. The most critical target in the cell is the DNA molecule responsible for cellular activities such as development, function and reproduction. Damage to cellular structures is manifested into possible cell death, failure to reproduce, or transmutation into new forms of cells. The latter cells may eventually develop into cancerous tumors. In the case of the germ cells, damage to the genes may introduce inheritable diseases, which may appear in future generations. This is the reason for not allowing pregnant women to work in a radiation environment. On the

[2] Additional information can be obtained from the report, *Safety and nutritional adequacy of irradiated food*, WHO, Geneva, 1994.

macroscopic level, the damage is cumulative and may immediately express itself in the form of "acute" reactions, such as skin redness or diarrhea; or take years to cause “chronic” problems such as leukemia or cancers.

Despite these known risks, ionizing radiation is routinely used as an integral part of modern medicine. This is because the benefit has been found to outweigh the risks associated with the judicious use of ionizing radiation.

1.10 Safe Handling of Radiation and Sources

While patients and medical personnel are being exposed to radiation during medical procedures, the medical benefits outweigh the risks involved. The risks are further reduced if the radiation is applied with prudence to minimize unwarranted radiation exposure. Today, radiation exposure to personnel and patients is greatly reduced as a result of better understanding of the biological effects of radiation and better equipment as well as legal mandates. Education and training are important to ensure the proper use of radiation. The implementation of radiation protection methods has minimized unwarranted radiation exposure. The radiation protection methods include **minimizing time spent in a radiation environment, staying behind a radiation shield, and standing as far away from the radiation sources** as possible. These methods will be discussed further in the health physics chapters. The proper use of radiation producing equipment also helps in reducing unnecessary exposure. Regulatory guidelines and quality management programs provide the means of compliance for the safe use of radiation in medical procedures. Ultimately, the responsibility for the safe use of radiation falls primarily on the radiologic technologists, nuclear medicine technologists, radiation therapists, medical physicists, radiation oncologists, radiologists, and nuclear medicine physicians.

The procedure for safe handling of radiation will depend on the amount and types of radiation involved. For photon beams, high atomic number shielding materials such as lead are used. Shielded vaults or treatment rooms built of concrete and lead are used to house linear accelerators because of the high radiation intensity. Patients receiving large therapeutic doses of radioactive drugs or implanted radioactive sources may pose significant risks of radiation exposure to others. As such they may be confined to their hospital rooms until the radioactivity decays to a level that the exposure is below the regulatory releasable limit. Compared to therapeutic procedures, the radiation sources used in diagnostic procedures are generally weaker or administered in small traceable amounts with short half-lives.

From the health physics standpoint, beta particles, which do not penetrate deeper than the skin is of less concern than the bremsstrahlung radiation produced from the shielding material. Shielding of the beta particles must also take into account the need to shield bremsstrahlung radiation. The most effective shielding incorporates the use of plastic to absorb the beta particles and enclosing the plastic in lead to absorb the bremsstrahlung radiation.

1.11 Historical Perspectives of Radiological Physics

An experiment, which was designed to study cathode rays, resulted in the discovery of x-rays by Wilhelm Conrad Roentgen (1845–1923) on November 8, 1895. To perform the experiment, the cathode ray tube (also called Hittorf–Crooks or Crookes tube) was carefully shielded with black cardboard to prevent blue light emitted by the cathode tube from escaping. However when the room was darkened, Roentgen noticed an unusual faint greenish light glimmering momentarily from a nearby table. His repeated excitation of the cathode tube and his awareness of the greenish luminescence allowed him to trace the source to a fluorescent screen which is a piece of cardboard coated with **barium platinocyanide** on the table. Since Roentgen was aware that cathode rays travel only a few centimeters in air, he realized that the observed effects were from a new radiation phenomenon. Further investigations led him to name this radiation x-rays, where the letter "x" stands for unknown quantity. The first x-ray transmission image was produced when Roentgen observed an image of his fingers and bones while he was placing a piece of metal in front of a paper screen to attempt to evacuate the cathode tube. In 1901, Roentgen was awarded the first Nobel Prize in Physics for his discovery of x-rays.

In 1896, the French physicist Henri Antoine Becquerel (1852–1908) discovered spontaneous radioactivity. Becquerel placed a piece of uranium ore on a package of undeveloped photographic plates wrapped in black paper for protection. On development of the photographic plate, he was amazed to see an image of the uranium ore that had been placed on the package. He deduced that this effect was caused by some unknown kind of radiation coming from the ore.

In 1898, Marie and Pierre Curie (Marie Curie, 1867–1934; Pierre Curie, 1859–1906) succeeded in isolating a portion of 1 gram of radioactive substance from about 1 ton of pitchblende (uranium ore) after laborious efforts. The radioactive substance was named polonium in honor of Madame Curie's native Poland. For their work, they were awarded the Nobel Prize in physics jointly with Henri Antoine Becquerel in 1903. Later in the same year, they extracted radium. In 1911, Madame Curie was awarded the Nobel Prize for isolating the natural radioactive element radium.

The English physicists, Ernest Rutherford and Frederic Soddy, observed the first artificial atomic disintegration. In 1902, they proposed that radioactive elements disintegrate and in the process emit various types of radiation resulting in the formation of new elements. This process is called **transmutation**.

Ernest Rutherford also discovered that a magnetic field could separate a radiation beam into alpha particles and beta particles. Later, Paul Willard found another form of radiation called gamma rays.

Madame Curie's oldest daughter, Irene Curie Joliot and her husband Frederic Joliot first produced artificial radioactivity in 1934. In the experiment, aluminum was bombarded with alpha particles. After the bombardment, the aluminum foil was found to remain radioactive with the emission of radiation like other radioelements.

The German scientists, Otto Hahn and Fritz Strassmann discovered nuclear fission in 1938. They found that uranium when bombarded by neutrons produced radioactive nuclei of barium-141. In 1939, Otto Frish and Lisa Meitner working in Scandinavia suggested that the uranium was undergoing nuclear fission where the nucleus splits into smaller nuclei roughly half the size of the uranium nucleus.

Leo Szilard and Enrico Fermi demonstrated the possibility of sustaining chain reaction of nuclear fission in 1942. The chain reaction occurred as a result of the bombardment of uranium with neutrons. The byproducts were additional neutrons and nuclei of comparable sizes. These neutrons in turn bombarded the uranium causing a chain reaction. The successful demonstration of the chain reaction led to the building of the first nuclear reactor at the University of Chicago.

The first use of nuclear fission was in the building of the fission bomb called the **atomic bomb**. In the early 1940s, nuclear fission technology was available to Germans in World War II. It was believed that the German scientists were trying to build the atomic bombs. Hitler banned the sale of uranium from the Czech mines after taking over the territories. Physicists in the United States were alarmed and warned the nation that the production of an atomic bomb was of utmost urgency. The physicists convinced Albert Einstein to write a letter to President Roosevelt about the possibility of producing a nuclear bomb and that the Germans had developed such a bomb. Roosevelt responded by authorizing the **Manhattan Project** to examine whether building such a bomb was feasible. Well-known physicists from across the country were recruited to work at a secret laboratory in Los Alamos, New Mexico under the direction of J. Robert Oppenheimer (1904 – 1967) to examine this possibility. The first fission bomb was successfully tested in July 1945 in a New Mexico desert. In early August 1945, a fission bomb using uranium was dropped on Hiroshima and a second bomb using plutonium was dropped on Nagasaki, ending World War II. However, the construction and the dropping of the bomb raised numerous questions and controversies among the physicists. This debate continues today.

1.12 Branches of Physics in Medicine

Physics is an experimental science that deals with the study of energy, matter, and their interactions. The word itself is a translation from the Latin word "physica" meaning natural science. Other branches of science are chemistry and biology. The word "science" is used to describe any methodological activity such as observation, identification, description, experimental investigation, and theoretical explanation of physical phenomena often referred to as the world around us. Since the methodology of science requires that a distinction be made between what is relevant and what is not, science essentially is a creativity of our human minds by modeling observed events in our universe. Because of this process, science was once known as natural philosophy with the creativity leading to the formulation of theories to explain observations.

The branch of physics that deals with radiation is called **radiation physics or radiological physics**. Radiation physicists can be found in research laboratories, national laboratories, nuclear power plants, and in hospitals using radiation for the diagnosis and treatment of diseases. A sub-branch of radiation physics is health physics. **Health physics** addresses the issue of radiation exposure to personnel working in the radiation environment. Health physicists can be found in any facility that uses radiation. On the other hand, **medical physics** is the sub-branch of physics that has found applications in the medical field. In the past, the term medical physicist and radiological physicist were used interchangeably. In general, the role of medical physicists is to oversee equipment performance, dosimetry, radiation safety, electronic data transfer, quality control, and quality assurance. As the fields become specialized, medical physics has also become subdivided into radiation oncology physics, diagnostic physics, and nuclear medicine physics.

Summary

1.1 Radiation refers to the propagation of radiant energy through space or a medium. The physical properties of radiation are odorless, tasteless, and invisible, making it impossible to detect using our senses. Radiation has both wave-like and particle-like properties. The principle of complementarity states that either the wave model or the particle model can be used at a time to understand a given experiment.

1.2 Radiation can be broadly classified as either electromagnetic radiation or particulate radiation. Electromagnetic radiation is a packet of energy that possesses no mass, no charge, and travels at the speed of light. Corpuscular or particulate radiation carries a rest mass. Radiation is classified according to its ability to ionize as ionizing and non-ionizing radiation. Ionizing radiation is further subdivided into directly ionizing and indirectly ionizing radiation. Directly ionizing radiation is radiation capable of directly disrupting the atomic structure of the medium, resulting in chemical change and biological damage.

1.3 Both photon and matter exhibit wave-like and particle-like behaviors. De Broglie postulated the latter phenomenon.

1.4 A photon is characterized as a quantum of electromagnetic energy propagating through space at the speed of light. It has no mass and no charge but possesses a spin of 1, angular momentum, and energy. The directions of the electric field and the magnetic field oscillate perpendicular to each other and to the direction of propagation. The energy, wavelength and frequency relationships of a photon are given by equations (1.1) and (1.2).

1.5 Typical particulate radiation found in medicine are alpha rays, beta rays, neutrons, and protons. The heaviest of these particles are alpha rays consisting of two neutrons and two protons. Negatrons, which posses a unit negative (−1e) charge and positrons, which possess a unit positive (+1e) charge, are both beta rays. One unit of charge is equal to 1.602×10^{-19} C. The proton and neutron are about 1836 times more massive than an electron.

1.6 The electromagnetic wave spectrum covers the range from radiowaves to gamma rays with wavelengths from 10^{+7} m to 10^{-13} m. All electromagnetic radiations are non-ionizing radiations except x-rays and gamma rays.

1.7 The type of radiation can be identified by its charge and penetrability properties. The direction of motion of the radiation as it passes through a magnetic field can be used to identify its charge property. The penetrability of the radiation is qualitatively described using inches of lead for gamma rays, inches of wood for beta particles, and thin piece of paper for alpha rays.

1.8 There are basically four radiological quantities: radiation exposure, absorbed dose, dose equivalent, and radioactivity. The unit of radiation exposure is charge per unit mass (C/kg) while the absorbed dose is energy per unit mass (ergs/gm). On the other hand, the unit of radioactivity is the number of disintegrations per second (dps). The equivalent dose is used in radiation protection to account for the radiobiological effects.

1.9 Most types of radiation are harmless, but ionizing radiation can cause injury to humans. Ionizing radiation alters the atomic and nuclear bonding and hence chemical bonding of molecules in the cells of living matter, causing damage and subsequent biological effects. In addition to biological effects, ionizing radiation can cause photographic effects, luminescence effects, ionizing effects, and thermoluminescence effects.

1.10 The rearrangement of the constituents of atoms and nuclei produces radiation. Characteristic radiation and Auger electrons are emitted as a result of the rearrangement of orbital electrons. The rearrangement of nucleons in the nuclei produces gamma rays. Besides gamma rays, alpha particles, beta particles, protons, and neutrons may be emitted during nuclear transformations. For the purpose of comparison, we say that x-rays are produced in the atoms while gamma rays are produced in the nuclei. Beyond the origins, x-rays and gamma rays are indistinguishable.

1.11 A list of formulas:

Electromagnetic radiation: $E = h\nu$

$c = \lambda \nu$

$$E\,(\text{keV}) = \frac{12.4}{\lambda\,(\text{Å})}$$

Relativity mass: $m = \dfrac{m_o}{(1-\beta^2)^{1/2}}$; $\beta = \dfrac{v}{c}$

Einstein mass–energy equivalence: $E = m c^2$

Study Guide

1.1 In your own words, define the following terms:
(a) PET (b) SPECT

(c) radiation
(d) corpuscular or particulate radiation
(e) x-rays
(f) gamma rays
(g) teletherapy
(h) brachytherapy
(i) laser
(j) ionization
(k) excitation
(l) photon
(m) quanta
(n) scientific notation
(o) de Broglie wave
(p) relativistic mass
(q) neutrinos
(r) mu mesons
(s) negatron
(t) positron
(u) equivalent dose
(v) absorbed dose
(w) radiation exposure
(x) radioactivity

1.2 Identify four types of electromagnetic radiation used in medical imaging.

1.3 Identify three types of benign disease treated with ionizing radiation.

1.4 Identify two types of particulate radiation used in medicine.

1.5 List two properties that differentiate between particulate and electromagnetic radiation.

1.6 Classify the following types of radiation — alpha particle, beta particle, gamma ray, proton, and neutron — as either ionizing or non-ionizing radiation and either directly or indirectly ionizing radiation.

1.7 Identify two types of non-ionizing radiation.

1.8 What is the difference between a 100 keV x-ray and a 100 keV gamma ray?

1.9 Identify the difference between 6.4 MHz radiowaves and 6.4 MHz ultrasound waves.

1.10 Arrange in order the components of electromagnetic wave spectrum according to their approximate frequencies.

1.11 What is an angstrom?

1.12 Compare the radiation properties with respect to mass, charge, and composition (protons, neutrons, electrons) of alpha particle, beta particle, gamma ray, proton, neutron, electron, and positron.

1.13 What is the difference between electron, negatron, positron, and beta particle?

1.14 What is the mass in kilogram of an electron and a proton?

1.15 Explain how one would identify the types of radiation based on their charge and penetrability properties.

1.16 Identify the SI units of (a) exposure, (b) absorbed dose, (c) equivalent dose, and (d) radioactivity.

1.17 Radiation exposure rate (R/s) is being replaced with air kerma rate, which is the absorbed dose in air (cGy/s). Which unit has a lower numerical value?

1.18 List three effects of ionizing radiation.

1.19 List three methods of minimizing radiation exposure to a person in a radiation environment.

1.20 Understand the historical development leading to their discoveries by Roentgen, Becquerel, and Madame Curie.

1.21 Does bremsstrahlung radiation have a continuous or discrete energy spectrum?

*1.22 Explain how do you convert one roentgen into absorbed dose in tissue?

*1.23 Explain the circumstance under which absorbed dose is independent of the type of medium and dependent on the nature of the medium.

*1.24 Differentiate between radiation sources and radioactive sources.

Problems

1.1 Compute the wavelength in Å of ultraviolet light whose frequency is 3×10^{16} Hz.

1.2 What is the frequency of radiowaves if the wavelength is 3×10^{3} m?

1.3 The wavelength range of visible light is from 4000 Å – 7000 Å. What is the energy in eV of green light whose wavelength is 5000 Å?

1.4 Write the measured values of 3.1×10^{6} Hz and 5.0×10^{-6} m using prefixes.

1.5 Compute the speed and mass of a 100 keV photon.

1.6 Calculate the wavelength in Å of photons whose energies are (a) 1 eV, (b) 1 keV, and (c) 1 MeV.

1.7 Calculate the frequency in Hz of photons whose energies are (a) 1 eV, (b) 1 keV, and (c) 1 MeV.

1.8 Calculate the momentum of a particle whose wavelength is 1 angstrom.

1.9 Express the dose of 0.05 Gy in rads.

1.10 Express 550 rads in terms of Gy.

1.11 During a radiation treatment 200 rad was delivered to 100 gm of tissue. What dose would 1 gm of tissue have received?

1.12 During a calorimetric investigation, 10 joules of energy were imparted onto a kilogram of water. Compute the radiation dose in cGy.

1.13 Express the radiation exposure of 2 R/min in SI unit (C/kg·min).

1.14 Express the radioactivity of 15 mCi in SI unit (Bq).

1.15 A radioactive sample has a disintegration rate of 8.3×10^{6} Bq. Express this activity in microCuries (μCi).

*1.16 Compute the wavelength of a 100 keV electron (electron mass = 9.10908×10^{-31} kg).

*1.17 Show that the phase velocity, which is the product of wavelength and frequency of a particle is given as $\lambda\nu = c^2/v$, where v is the velocity of a particle. Also show that in the non-relativistic region where the rest mass is neglected and the total energy is the kinetic energy, the phase velocity is equal to v/2.

*1.18 Show that the average energy needed to produce an ion pair in air is 33.97 eV.

*1.19 Calculate the number of photons having 1 MeV needed to produce 1 rad. Assume that the energy absorption efficiency (energy absorption coefficient) is 0.03.

Multiple Choice Questions

Select the one correct answer.

1.1 Which modality does NOT utilize electromagnetic radiation in the formation of images?
a) radiography
b) ultrasound imaging
c) magnetic resonance imaging
d) positron emission tomography
e) none of the above

1.2 Which statement is NOT true of photons?
a) Photons have no charge.
b) Photons have no mass.
c) Photon energy is given as $E = h\nu$ where ν is the frequency.
d) Photons travel at the speed of light.
e) none of the above.

1.3 A **fermi** (1.0×10^{-15} m) is a unit commonly used in nuclear physics to express the size of the mass. The SI unit prefix is
a) kilometer.
b) millimeter.
c) micrometer.
d) nanometer.
e) femtometer.

1.4 Express 161.5 cm in scientific notation
a) 16.15×10^1 cm
b) 1.615×10^2 cm
c) 16.15×10^3 m
d) 1.615×10^4 m
e) 0.1615×10^5 m

1.5 Which of the following is NOT a particulate radiation?
a) proton
b) neutron
c) β particle
d) α particle
e) none of the above

1.6 Which of the following statements is NOT true about corpuscular radiation?
a) Corpuscular radiation is particle radiation.
b) Neutron is an example of non-charged particle radiation.
c) Charged particles are alpha particles, beta particles, and protons.
d) Charged particles can cause ionization and excitation of target atoms.
e) none of the above.

1.7 What is the speed of a photon whose wavelength is 4×10^{-8} m compared to the speed of light, c?
a) speed is less than c
b) speed is equal to c
c) speed is more than c
d) speed is c/λ
e) none of the above

1.8 All these particles have the same mass except the
a) positron.
b) negatron.
c) electron.
d) neutron.
e) beta particle.

1.9 Which of the following is NOT true of β particles?
a) Negatron and positron are alike except for the charge.
b) The charge of a negatron is $+1.60 \times 10^{-19}$ C.
c) Except for their origins, negatron and electron are identical.
d) Positron is unstable or short lived.
e) none of the above.

1.10 Which of the following radiation has the shortest range in tissue?
a) alpha
b) beta
c) positron
d) neutrino
e) gamma

1.11 Which of the following is INCORRECT about Roentgen?
a) It is a unit of exposure and not a unit of absorbed dose.
b) It is applicable to both particulate and electromagnetic radiation.
c) It is applicable to photons with energies less than 3 MeV.
d) It is applicable only in air.
e) none of the above.

1.12 Spontaneous activity was discovered by
a) W.C. Roentgen.
b) H.A. Becquerel.
c) Marie Curie.
d) E. Rutherford.
e) none of the above.