PHYSICS OF RADIATION THERAPY

Assist. Prof. Dr. Basim AL-Juboury

BASIC PHYSICS STRUCTURE OF MATTER

1-1 THE ATOM

All matter is composed of individual entities called elements. Each element is distinguishable from the others by the physical and chemical properties of its basic component—the atom. Originally thought to be the “smallest” and “indivisible” particle of matter, the atom is now known to have a substructure and can be “divided” into smaller components. Each atom consists of a small central core, the nucleus, where most of the atomic mass is located and a surrounding “cloud” of electrons moving in orbits around the nucleus. Whereas the radius of the atom (radius of the electronic orbits) is approximately 10 ^−10 m, the nucleus has a much smaller radius, namely, about 10^-15 m. Thus, for a high-energy electron, photon, or a particle of size comparable to nuclear dimensions, it will be quite possible to penetrate several atoms of matter before a collision happens. As will be pointed out in the chapters ahead, it is important to keep track of those particles or photons that have not interacted with the atoms and those that have suffered collisions.

1-2 THE NUCLEUS

The properties of atoms are derived from the constitution of their nuclei and the number and the organization of the orbital electrons.

The nucleus contains two kinds of fundamental particles: protons and neutrons. Whereas protons are positively charged, neutrons have no charge. Because the electron has a negative unit charge (1.602×10^{-19} C) and the proton has a positive unit charge, the number of protons in the nucleus is equal to the number of electrons outside the nucleus of an electrically neutral atom.

An atom is completely specified by the formula ${}_{Z}^{A}X$, where X is the chemical symbol for the element; A is the mass number, defined as the number of nucleons (neutrons and protons in the nucleus); and Z is the atomic number, denoting the number of protons in the nucleus (or the number of electrons outside the nucleus). An atom represented in such a manner is also called a nuclide. For example, ^{1}H and ${}_{2}^{4}He$ represent atoms or nuclei or nuclides of hydrogen and helium ,respectively.

On the basis of different proportions of neutrons and protons in the nuclei, atoms have been classified into the following categories: isotopes, atoms

having nuclei with the same number of protons but different number of neutrons; isotones, atoms having the same number of neutrons but different number of protons; isobars, atoms with the same number of nucleons but different number of protons; and isomers, atoms containing the same number of protons as well as neutrons. The last category, namely isomers, represents identical atoms except that they differ in their nuclear energy states. For example, ${}^{131m}_{54}Xe$ (m stands for metastable state) is an isomer of ${}^{131}_{54}Xe$.

Certain combinations of neutrons and protons result in stable (nonradioactive) nuclides than others. For instance, stable elements in the low atomic number range have an almost equal number of neutrons, N, and protons, Z. However, as Z increases beyond about 20, the neutron to proton ratio for stable nuclei becomes greater than 1 and increases with Z. This is evident in Figure 1.1, which shows a plot of the number of neutrons versus protons in stable nuclei.

Nuclear stability has also been analyzed in terms of even and odd numbers of neutrons and protons. of about 300 different stable isotopes, more than half have even numbers of protons.

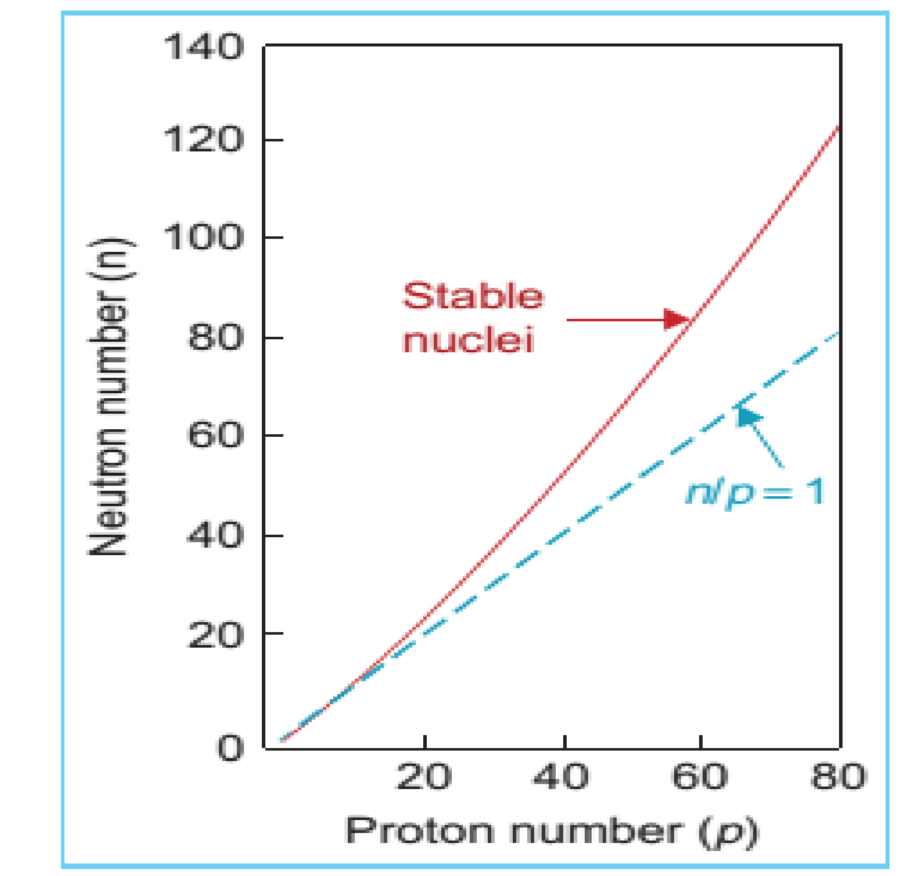


Figure 1.1. a plot of neutrons versus protons in stable nuclei.

1.3 ATOMIC MASS AND ENERGY UNITS

Masses of atoms and atomic particles are conveniently given in terms of atomic mass unit (amu) .An amu is defined as 1/12 of the mass of a ${}^{12}_{6}C$ atom. Thus, the ${}^{12}_{6}C$ atom is arbitrarily assigned the mass equal to 12 amu. In basic units of mass 1 amu = 1.66×10^{-27} kg

The mass of an atom expressed in terms of amu is known as atomic mass or atomic weight.

Another useful term is gram atomic weight, which is defined as the mass in grams numerically equal to the atomic weight. According to Avogadro's law, every gram atomic weight of a substance contains the same number of atoms. The number, referred to as Avogadro number or Avogadro constant (N_A), has been measured by many investigators, and its currently accepted value is $6.0221 \text{ X } 10^{23}$ atoms per gram atomic weight (or mole).

- From the previous definitions, one can calculate other quantities of interest such as the number of atoms per gram, grams per atom, and electrons per gram. Considering helium as an example, its atomic weight (A_W) is equal to 4.0026.

Therefore,

$$\text{Number of atoms/g} = \frac{N_A}{A_W} = 1.505 \times 10^{23}$$

$$\text{Grams/atom} = \frac{A_W}{N_A} = 6.646 \times 10^{-24}$$

$$\text{Number of electrons/g} = \frac{N_A \cdot Z}{A_W} = 3.009 \times 10^{23}$$

The masses of atomic particles, according to the amu, are electron = 0.000548 amu, proton= 1.00727 amu, and neutron = 1.00866 amu.

Because the mass of an electron is much smaller than that of a proton or neutron and protons and neutrons have nearly the same mass, equal to approximately 1 amu, all the atomic masses in units of amu are very nearly equal to the mass number. However, it is important to point out that the mass of an atom is not exactly equal to the sum of the masses of constituent particles.

- The basic unit of energy is joule (J) and is equal to the work done when a force of 1 newton acts through a distance of 1 m. The newton, in turn, is a unit of force given by the product of mass (1 kg) and acceleration (1 m/s^2). However, a more convenient energy unit in atomic and nuclear physics is electron volt (eV), defied as the kinetic energy acquired by an electron in passing through a potential difference of 1 V. It can be shown that the work done in this case is given by the product of potential difference and the charge on the electron. Therefore, we have:
- $1eV = 1\ V \times 1.602 \times 10^{-19}\ C = 1.602 \times 10^{-19}\ J$
- Multiples of this unit are 1keV = 1,000 eV
- 1million eV (MeV) = 1,000,000 eV
- According to Einstein's principle of equivalence of mass and energy, a mass m is equivalent to energy E and the relationship is given by
- $E = mc^2$ where c is the velocity of light (3×10^8 m/s).

For example, a mass of 1 kg, if converted to energy ,is equivalent to

$E = 1\ \text{kg} \times (3 \times 10^8\ \text{m/s})^2 \quad = \quad 9X\ 10^{16}\ \text{J} = 5.62 \times 10^{29}\ \text{MeV}$

The mass of an electron at rest is sometimes expressed in terms of its energy equivalent (E_0) .Because its mass is 9.1×10^{-31} kg, we have:

$E_0 = 0.511$ MeV

Another useful conversion is that of amu to energy. It can be shown that

1amu = 931.5 MeV

we can see that the equivalent mass of any particle of total energy E (kinetic plus rest mass energy) is given by E/c^2.

The relationship between mass and velocity can be derived from Einstein's theory of relativity. If m is the mass of a particle moving with velocity υ and m_0 is its rest mass, then

$$m = \frac{m_0}{\sqrt{1 - \upsilon^2/c^2}}$$

The kinetic energy (E_k) is given by

$$E_k = mc^2 - m_0c^2 = m_0c^2\left[\frac{1}{\sqrt{1 - \frac{\upsilon^2}{c^2}}} - 1\right]$$

It should be noted that the relativistic effect of velocity on mass becomes important when a particle travels with a velocity comparable to that of light.

1.4: DISTRIBUTION OF ORBITAL ELECTRONS

According to the model proposed by Niels Bohr in 1913, the electrons revolve around the nucleus in specific orbits and are prevented from leaving the atom by the centripetal force of attraction between the positively charged nucleus and the negatively charged electron.

On the basis of classical physics, an accelerating or revolving electron must radiate energy.

This would result in a continuous decrease of the radius of the orbit with the electron eventually spiraling into the nucleus. However, the data on the emission or absorption of radiation by elements reveal that the change of energy is not continuous but discrete.

To explain the observed line spectrum of hydrogen, Bohr theorized that the sharp lines of the spectrum represented electron jumps from one orbit down to another with the emission of light of a particular frequency or a quantum of energy.

He proposed two fundamental postulates: (a) electrons can exist only in those orbits for which the angular momentum of the electron is an integral multiple of $h/2\pi$,where h is the Planck's constant (6.626×10^{-34} J.sec); and (b) no energy is gained or lost while the electron remains in any one of the permissible orbits.

The arrangement of electrons outside the nucleus is governed by the rules of quantum mechanics and the Pauli exclusion principle (not discussed here). Although the actual configuration of electrons is rather complex and dynamic, one may simplify the concept by assigning electrons to specific orbits.

Electron orbits can also be considered as energy levels. The energy in this case is the potential energy of the electrons. With the opposite sign it may also be called the binding energy of the electron.

1.5 NUCLEAR FORCES

As discussed earlier, the nucleus contains neutrons that have no charge and protons with positive charge. But how are these particles held together, in spite of the fact that electrostatic repulsive forces exist between particles of similar charge? Earlier, in Section 1.3, the terms mass defect and binding energy of the nucleus were mentioned. It was then suggested that the energy required to keep the nucleons together is provided by the mass defect. However, the nature of the forces involved in keeping the integrity of the nucleus is quite complex and will be discussed here only briefly. There are four different forces in nature. These are, in the order of their strengths: (a) strong nuclear force, (b) electromagnetic force, (c) weak nuclear force, and (d) gravitational force.

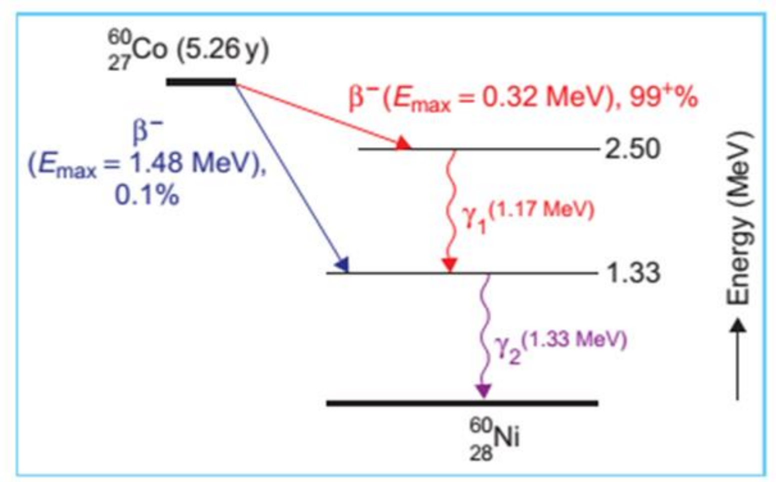
Of these, the gravitational force involved in the nucleus is very weak and can be ignored. The electromagnetic force between charged nucleons is quite strong, but it is repulsive and tends to disrupt the nucleus. A force much larger than the electromagnetic force is the strong nuclear force that is responsible for holding the nucleons together in the nucleus.

The weak nuclear force is much weaker and appears in certain types of radioactive decay (e.g., β decay).

The strong nuclear force is a short-range force that comes into play when the distance between the nucleons becomes smaller than the nuclear diameter (~10^{-15} m). If we assume that a nucleon has zero potential energy when it is an infinite distance apart from the nucleus, then as it approaches close enough to the nucleus to be within the range of nuclear forces, it will experience strong attraction and will “fall” into the potential well. This potential well is formed as a result of the mass defect and provides the nuclear binding energy. It acts as a potential barrier against any nucleon escaping the nucleus.

1.6 NUCLEAR ENERGY LEVELS

The shell model of the nucleus assumes that the nucleons are arranged in shells, representing discrete energy states of the nucleus similar to the atomic energy levels. If energy is imparted to the nucleus, it may be raised to an excited state, and when it returns to a lower energy state, it will give off energy equal to the energy difference of the two states. Sometimes the energy is radiated in steps, corresponding to the intermediate energy states, before the nucleus settles down to the stable or ground state.



Energy level diagram for the decay of $^{60}_{27}Co$ nucleus.

1.7 PARTICLE RADIATION

The term radiation applies to the emission and propagation of energy through space or a material medium. By particle radiation, we mean energy propagated by traveling corpuscles that have a definite rest mass and within limits have a definite momentum and defined position at any instant. However, the distinction between particle radiation and electromagnetic waves, both of which represent modes of energy travel, became less sharp when, in 1925, de Broglie introduced a hypothesis concerning the dual nature of matter. He theorized that not only do photons (electromagnetic waves) sometimes appear to behave like particles (exhibit momentum) but also material particles such as electrons, protons, and atoms have some type of wave motion associated with them (show refraction and other wavelike properties).

Besides protons, neutrons, and electrons discussed earlier, many other atomic and subatomic particles have been discovered. These particles can travel with high speeds, depending on their kinetic energy, but never attain exactly the speed of light in a vacuum. Also, they interact with matter and produce varying degrees of energy transfer to the medium.

1.8 ELEMENTARY PARTICLES

Elementary or fundamental particles are particles that are not known to have substructure .In the past, the name was given to protons, neutrons, and electrons. With the discovery that protons and neutrons have substructure (quarks), they are no longer considered fundamental particles. The following discussion of elementary particles is presented here for general interest.

There are two classes of particles: fermions and bosons. Fermion is a general name given to a particle of matter or antimatter that is characterized by spin in odd half integer quantum units of angular momentum (1/2, 3/2, 5/2,…). Boson is a general name for any particle with a spin of an integer number (1, 2, 3, …).

The fundamental particles of matter (fermions) are of two kinds: quarks and leptons. There are six types of each, as listed below:

- Quarks: up (u), down (d), charm (c), strange (s), top (t), and bottom (b);
- Leptons: electron (e), electron neutrino (ν_e) ,muon (μ), muon neutrino (ν_μ) ,tau (τ), and tau neutrino (ν_τ).

Besides the above 12 elementary particles of matter, there are 12 corresponding elementary particles of antimatter. This follows the principle discovered by Paul Dirac (1928) which states that for every particle of matter there must be another particle of antimatter with the same mass but opposite charge. So there are six antiquarks and six antileptons.

Quarks are the building blocks of heavier particles, called hadrons (neutrons, protons , mesons, etc.). For example, it takes three quarks (u, u, d) to make a proton and three quarks (u, d, d) to make a neutron. These quarks are held together by field particles called gluons, the messenger particles of the strong nuclear force.

There are 13 messenger particles or bosons that mediate the four forces of nature. They are listed below:

Electromagnetism	photon (γ)
Strong force	eight gluons
Weak force	W^+, W^-, Z^o
Gravity	graviton (not yet detected)

Whereas matter particles (fermions) can attain high energy or speeds, they cannot quite attain the speed of light. When their speed reaches close to that of light, further acceleration increases their energy through an increase in their mass rather than their speed

1.9 ELECTROMAGNETIC RADIATION

A. WAVE MODEL

Electromagnetic radiation constitutes the mode of energy propagation for such phenomena as light waves, heat waves, radio waves, microwaves, ultraviolet rays, x-rays, and γ rays. These radiations are called “electromagnetic” because they were fist described, by Maxwell, in terms of oscillating electric and magnetic fields. As illustrated in Figure 1.7, an electromagnetic wave can be represented by the spatial variations in the intensities of an electric field (E) and a magnetic field (H), the fields being at right angles to each other at any given instant. Energy is propagated with the speed of light (3×10^8 m/s in vacuum) in the Z direction. The relationship between wavelength (l), frequency (n), and velocity of propagation (c) is given by c = $n\lambda$

The wave nature of the electromagnetic radiation can be demonstrated by experiments involving phenomena such as interference and diffraction of light. Similar effects have been observed with x rays using crystals which possess interatomic spacing comparable to the x ray wavelengths. However, as the wavelength becomes very small or the frequency becomes very large, the dominant behavior of electromagnetic radiations can only be explained by considering their particle or quantum nature.

B. QUANTUM MODEL

To explain the results of certain experiments involving interaction of radiation with matter, such as the photoelectric effect and the Compton scattering, one has to consider electromagnetic radiations as particles rather than waves. The amount of energy carried by such a packet of energy, or photon, is given by $E = h\nu$

where E is the energy (joules) carried by the photon, h is the Planck's constant (6.626×10^{-34} Jsec) and ν is the frequency (cycles/s). By combining above Equations, we have

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

If E is to be expressed in electron volts (eV) and λ in meters (m), then, since 1 eV = 1.602×10^{-19}J:

$$E = \frac{1.24 \, x \, 10^{-6}}{\lambda}$$

The above equations indicate that as the wavelength becomes shorter or the frequency becomes larger, the energy of the photon becomes greater.