## 1. Structure of the atom and Terminology

All matter is comprised of **atoms**. An atom is the smallest unit into which a chemical element can be broken down without losing its chemical identity. The atomic nucleus is comprised of **protons** and **neutrons**. Collectively the particles are known as **nucleons**.

In simple solar-system or Bohr model (according to Niels Bohr) of the atom, electrons orbit around a dense, positively charged nucleus at fixed distances. In this model of atom, each electron occupies a discrete energy state in a given electron shell. These electron shells are assigned the letters K, L, M, … with K denoting the innermost shell, in which the electrons have the lowest energies.

The energy required to completely remove an electron from a given shell in an atom is called the binding energy of that shell (binding energy is greatest for the innermost shell). The energy required to move an electron from an inner to an outer shell is exactly equal to the difference in binding energies between the two shells.

When orbital electrons are exposed to energy such as electromagnetic radiation or electrical forces of energetic charge particles (protons, beta or alpha particles) it leads to excitation or ionization:

**Ionization** occurs when the energy transferred to an orbital electron is sufficient to cause an electron to be ejected from the atom, thus creating an ion pair (a negatively charged electron and a positively charged atom).

**Excitation** is process when the energy transferred to bound electron is only sufficient to bump an electron from an inner to an outer shell of the atom.

Following excitation, an electron from an outer shell promptly moves in to fill the vacancy and energy is release in the process. The energy released, when an electron drops from an outer to an inner shell, is exactly equal to the difference in binding energies between the two shells. The energy may appear as a photon of electromagnetic radiation. Electron binding energy differences have exact characteristic values for different elements, therefore, the photon emissions are called **characteristic radiation** or **characteristic x rays**.

As an alternative to characteristic x-ray emission, the atom may undergo a process known as the **Auger effect**. In the Auger effect, an electron from an outer shell again fills the vacancy, but the energy released in the process is transferred to another orbital electron. This electron is emitted from the atom instead of characteristic radiation and is called Auger electron.

## 2. The nucleus and Radioactive decay

The number of protons in an atom is called the **atomic number** and is represented by the letter Z. Atomic number Z characterizes chemical elements. The name given to the number of neutrons in an atom is the **neutron number N**. **The mass number A** is the total number of nucleons in the nucleus. That is, A is equal to the sum of Z and N.

**A nuclide** is any individual atomic species, characterized by a specific number of neutrons and protons. Nuclides that have the same atomic number Z, but different neutron number are called **isotopes**. Some nuclides are radioactive and are called **radionuclides**. Radionuclides are inherently unstable and undergo radioactive decay.

**Radioactive decay** is a process in which an unstable nucleus transforms into a more stable one by emitting particles and (or) photons, releasing energy in the process. We call an unstable radioactive nucleus the parent and the more stable product nucleus the daughter. In many cases, the daughter also is radioactive and undergoes further radioactive decay. Radioactive decay is **spontaneous** process. In this chapter we discuss the general characteristic of various modes of radioactive decay.

In **decay by $\alpha$-particle** emission, the nucleus ejects alpha particle, which consists of two neutrons and two protons (essentially a $^4$He nucleus). The alpha particle is emitted with kinetic energy usually between 4 - 8 MeV. Although quite energetic, alpha particle have very short ranges in solid materials, for example, less than 0,1 mm in human tissues.

**Radioactive decay by $\beta^-$ emission** is a process in which, essentially, a neutron in the nucleus is transformed into a proton ($p^+$), an electron ($e^-$) and an antineutrino ($\tilde{v}$).

$$n^0 \rightarrow p^+ + e^- + \tilde{\nu} + E$$

The proton remains in the nucleus, but the electron and the antineutrino are ejected from the nucleus. The electron is called a $\beta^-$ particle. The antineutrino ($\tilde{\nu}$) is a “particle” having no mass or electrical charge. It undergoes virtually no interactions with matter and therefore is essentially undetectable. The energy (E) released in $\beta^-$ decay is shared between the $\beta^-$ particle and the antineutrino. $\beta^-$-particle energy receives from 0 to maximum possible energy from the decay process.

In radioactive decay **by $\beta^+$ emission**, a proton in the nucleus is transformed into a neutron ($n^0$), a positron ($e^+$) and a neutrino ($\upsilon$):

$$p^+ \rightarrow n^0 + e^+ + \nu + E$$

(A positron is the antiparticle of and ordinary electron). The neutron remains in the nucleus but a positron and a neutrino are ejected from the nucleus.

**Electron capture** decay looks like “inverse $\beta^-$ decay”. An orbital electron is “captured” by the nucleus and combines with a proton to form a neutron and a neutrino:

$$p^+ + e^- \rightarrow n^0 + \nu + E$$

The neutron remains in the nucleus while the neutrino is emitted from the nucleus and carries away some of the transition energy. The remaining energy appears in the form of characteristic X rays and Auger electrons, which are emitted by the daughter product when the resulting orbital electron vacancy is filled.

**Gamma emission** is not a primary decay process but usually accompanies alpha and beta decay. Typically this type of radiation arises when the daughter product resulting from alpha or beta decay is formed in an excited state. This excited state returns very rapidly ($< 10^{-9}$ s) to the ground state through the emission of a gamma photon. The average lifetimes of excited states range from $10^{-16}$ s to more than 100 y. Excited state that exist longer than $10^{-12}$ s is defined to be in a metastable or

isomeric state (denoted by m). The decay process from this excited state is known as an **isomeric transition** (IT, e.g. Tc-99m).
The name gamma was given to this radiation, before its physical nature was understood, because it was the third (alpha, beta, gamma) type of radiation discovered. A gamma ray is a photon (energy) emitted by an excited nucleus.

As an alternative to gamma ray emission is decay by **internal conversion.** In this process, the nucleus decays by transferring energy to an orbital electron, which is ejected instead of the gamma ray. It is as if the gamma ray were "internally absorbed" by collision with the orbital electron. The ejected electron is called a **conversion electron.** The orbital vacancy created by internal conversion is rapidly filled with an outer-shell electron, accompanied by emission of characteristic X-rays or Auger electrons.

Internal conversion, like $\beta^-$ decay, results in the emission of electrons. The important differences are that in $\beta^-$ decay, the electron originates from the nucleus, whereas in internal conversion it originates from an electron orbit.

Metastable radionuclides are of great importance in nuclear medicine. Because of their relatively long lifetimes, sometimes is possible to separate them from their radioactive parent and thus obtain a relatively "pure" source of gamma rays. The separation of the metastable daughter from its radioactive parent is accomplished by chemical means in a radionuclide "generator". Metastable nuclides always emit a certain number of conversion electrons, and thus they are not really "pure" gamma-ray emitters. Conversion electrons are almost totally absorbed within the tissue where they can cause substantial radiation dose to the patient.

**Activity** (A) is the number of decays per unit time. It has dimensions of disintegrations per second (dps). The System International (SI) unit of activity is the becquerel (Bq). One becquerel is defined as one radioactive decay per second. Nuclear medicine doses are generally greater and are expressed in the kilobecquerels (1 kBq = $10^3$ Bq), the megabecquerels (1 MBq = $10^6$ Bq) and the gigabecquerels (1 GBq = $10^9$ Bq).
The traditional unit for activity the curie (Ci) is defined as $3{,}7.10^{10}$ dps (*1 mCi = 37 MBq).*

Activity of radionuclides exponentially decreases with time (t): $A(t) = A_0 \cdot e^{\frac{-\ln 2}{T_{1/2}} t}$

where: $A_0$ is the acitivity at time zero and $T_{1/2}$ is the half-life of radionuclide.

**The physical half-life ($T_p$)** of radionuclide is the time required to decay to 50% of its initial activity level. The half-life cannot be affected by any physical or chemical conditions. The half-life time for individual radionuclides vary widely. For radionuclides used in nuclear medicine ranges from several seconds to several tens of days.

In nuclear medicine are also used the biologic half-life and effective half-life.

The **biologic half-life ($T_b$)** has nothing to do with radioactivity, but rather reflects the half-time for excretion of the material from the organ or whole body. For instance, the biologic half-life of $^{99m}$Tc-

MDP is the time it takes for one half of this radiopharmaceutical to be filtered and excreted by the kidneys and bladder.

The **effective half-life** (**$T_e$**) is a measurement that combines the two values above; it is the time required for one half of the initial radioactivity to disappear from an organ or the body both by excretion and physical decay. The effective half-life is always shorter than either the physical or biologic half-life and is calculated using the formula: $1/T_e = 1/T_b + 1/T_p$

## 3. Interaction of radiation with matter

The two most important general types of radiation emitted during radioactive decay are **charged particles** (such as alpha particles and beta particles) and an **electromagnetic radiation** (photons - such as gamma rays and X-rays). These radiation transfer their energy to matter as they pass through it. The principles of mechanism for energy transfer are ionization and excitation of atoms and molecules. Most of this energy is ultimately degraded into heat, however the ionization effect has other important consequences. For this reason, the radiations are called ionizing radiations. The processes by which ionizing radiations transfer their energy to matter will be discussed in this chapter.

### 3.1 Interactions of charged particles with matter

Charged particles (alpha, beta particles – electron or positrons…) interact with matter by electrical (i.e. coulombic) forces and lose kinetic energy via excitation, ionization and radiative losses.

When **alpha particles** collides with an orbital electron, its direction is virtually unchanged and it loses only a small fraction of its energy. As a result, their tracks tend to be straight lines, and they experience an almost continuous slowing down in which they lose small amount of energy in a large number of individual collisions. Thus, their path lengths (the distance the particles travel) and ranges (the depth of penetration of the particles in matter) are nearly equal.

The alpha particle has very short range in air as well as in soft tissue, that is why it constitute an almost negligible hazard as an external radiation source. Only a few centimeters of air, a sheet of paper, or a rubber glove provides adequate shielding protection. Even those particles that do reach the skin deliver a radiation dose only to the most superficial layers of skin. Alpha particle emitters become a radiation hazard only when ingested, then because of their densely ionizing nature, they become very potent radiation hazards.

By contrast, **electrons** (or positrons) can undergo large-angle deflections in collisions with orbital electrons and can lose a large fraction of their energy in these collisions. Electrons also undergo occasional collisions with nuclei in which they are deflected through large angles and bremsstrahlung photons are emitted. For these reasons, electron tracks are tortuous, their exact shape and length are unpredictable. The length of the path of an electron almost always exceeds its range.

Electron travels at a much faster speed than alpha particle for a given amount of kinetic energy. As a result, an electron spends a much briefer time in the vicinity of an atom than an alpha particle of similar energy does and therefore is less likely to interact with the atom. Also, an electron carries only one unit of electrical charge, versus two for alpha particle, and thus exerts weaker forces on orbital electrons. For these reasons, electrons lose their energy more slowly than alpha particles, they are much less densely ionizing, and they travel farther before they are stopped than alpha particles of similar energy. The range of beta particle is about 10 cm to 10 m in air and about 0,1 mm to 12 mm in soft tissues.

The fate of positrons ($e^+$) is unlike that of negatively charged electrons. After a positron has transferred most of its kinetic energy by ionization, excitation and radiative interactions, it combines with a free or loosely bound negative electron. This interaction is explosive, as the combined mass of the two particles is instantly converted into an energy in the form of two oppositely directed ($180^0$ from each other) **annihilation photons**, each of the energy 511 keV. This is referred to as an annihilation reaction.

Small charged particles such as electrons or positrons may be deflected by a nuclei as they pass through matter, which may be attributed to the positive charge of the atomic nuclei. This type of interaction generates x-radiation known as **bremsstrahlung,** which in German means “braking radiation.” The deceleration of the high-speed electrons in a x-ray tube produces the bremsstrahlung x-rays used in diagnostic imaging.

Bremsstrahlung can be important in some situations, such as the shielding of relatively large quantities of an energetic beta-particle emitter. The beta particles themselves are easily stopped by only a few millimeters of plastic, glass or aluminium. However the bremsstrahlung photons that they generate are much more penetrating and may require additional shielding around the primary beta-particle shielding. It is helpful in such situations to use a low-Z material, such as plastic, for the primary beta-particle shielding, and then to surround this with a higher-Z material, such as lead, for bremsstrahlung shielding. This arrangement minimizes bremsstrahlung production by the beta particles in the shielding material.

### 3.2 Interaction of photons (γ,X) with matter

X-rays is electromagnetic radiation following electron transition (characteristic x-ray) or accompanying electron deceleration (bremsstrahlung x-ray). Gamma rays are a form of electromagnetic radiation emitted from the nucleus as the excited state transitions to a lower energy state. Because the spacing of the energy states within the nucleus is usually considerably larger than those of atomic orbital electron energy states, electron transitions, gamma rays are often much more energetic than characteristic x-rays.

In the practice of nuclear medicine, where gamma rays with energies between 50 keV and 550 keV are used, Compton scattering is the dominant type of interaction in material with lower atomic numbers, such as human tissue (Z=7,5). The photoelectric effect is the dominant type of interaction in materials with higher atomic numbers, such as lead (Z=82). A third type of interaction of photons with matter, pair production, only occurs with very high photon energies (greater than 1020 keV) and is therefore not important in clinical nuclear medicine.

**The photoelectric effect** is the process when all of the incident photon energy is transferred to an orbital (generally inner-shell) electron, which is ejected from an atom. This electron is called a photoelectron and leaves the atom with an energy equal to the energy of incident, gamma ray is diminished by the binding energy of the electron. Following a photoelectric interaction, the atom is ionized, with an inner-shell vacancy. An outer-shell electron then fills the inner-shell vacancy and the excess energy is emitted as an x-rays or Auger electrons.

In **Compton scattering** the incident photon transfers part of its energy to an outer shell or (essentially) “free” electron, ejecting it from the atom. The scattered photon is emitted with some reduction in energy relative to the incident photon. Compton scattering results in ionization of the atom and a division of the incident photon´s energy between the scattered photon and the ejected electron. The ejected electron will lose its kinetic energy via excitation and ionization of atoms in the surrounding material. The Compton scattered photon may traverse the medium without interaction or may undergo subsequent interactions such as Compton scattering or photoelectric absorption. In X-ray transmission imaging and nuclear emission imaging, the detection of scattered photon by image receptors (or detectors) results in a degradation of image contrast and an increase in random noise.

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