4. MODES OF RADIOACTIVE DECAY

4.1 Alpha decay (α)

Radioactive nuclei having too many nucleons (n and p) often undergo alpha decay in order to achieve nuclear stability. Alpha particle has a mass of 4 units and a charge of +2 units and is, therefore, equivalent to $helium^{+2}$ ion. Alpha particles from radionuclides have energy ranging from 1.8 to 11.7 MeV.

In some cases, beta particles and gamma rays may also be emitted during alpha decay.

$$^{211}At \rightarrow {}^{207}Pb + \alpha$$

4.2 Beta (β^-) decay

Radioactive nuclei having neutrons in excess than what is needed for a stable configuration, mostly undergo β^- decay in order to achieve nuclear stability. Beta particles may be either negatively charged β^-, generally equivalent to electrons or positively charged β^+, also known as positrons. The emission of charged particles from the nucleus may be accompanied by the emission of gamma (γ) rays, which are energetic photons of electromagnetic radiation and do not have any charge or mass.

Emitted particles have the same mass and electrical charge of orbital electrons but they originate from the nucleus at the very instant of decay, when a neutron transforms to a proton. Such a transformation results in an increase in atomic number by 1 while the mass does not change significantly. The β^- decay phenomenon could be expressed as the following nuclear reaction:

$$n \rightarrow p + \beta^- + v^*$$

v* represents "anti-neutrino", a sub-atomic entity which does not have any mass or charge but which can possess energy. The β^- decay equation has to be balanced with respect to mass, charge, energy, momentum as well as spin. The v* is important for accounting for the conservation of momentum, spin and energy. Thus, unlike particles which are emitted with a single energy from a nuclide, β^- particles from a certain radionuclide could have varied energies, accompanied by the v* carrying a complementary amount of energy, with the total energy being same. β^- particles have energies in the range from a few keV to 14 MeV. For a given transition, β^- particles have a continuous spectrum of energies.

An example of beta decay is:

$$^{32}P \rightarrow {}^{32}S + \beta^- + v^*$$

4.3 Positron decay (β^+)

Radioactive nuclei having fewer neutrons than what is needed for a stable configuration undergo positron β^+ decay in order to achieve stability, if adequate energy is available from the nucleus for transformation of a proton to a neutron. Such a transformation results in a decrease in atomic number by 1, while the mass does not change significantly. The β^+ decay phenomenon could be expressed as the following nuclear reaction:

$$p \rightarrow n + \beta^+ + v$$

As in the case of β^- decay, in order to conserve momentum, spin and energy, a sub-atomic entity which does not have any mass or charge known as "neutrino" represented by v is also emitted, which carries some energy with it. Thus, like β^- particles, β^+ particles also have varying energies. However, unlike β^- particles, in the case of β^+ particle emission, the proton which is lighter is transformed to the heavier particle neutron, along with a positron, resulting in the generation of mass equivalent to 2 electrons (1 positron and another the difference between a neutron and a proton). This cannot be possible, unless energy is available for conversion into the mass equivalent to two electrons, which is 1.02 MeV. Hence, unlike β^- decay, β^+ decay can occur only when at least 1.02 MeV of energy is available. During transmutation, due to the changes in nuclear energy levels, certain nuclides have energy > 1.02 MeV, in which case, β^+ decay can occur. The energy in excess of 1.02 MeV is shared by the β^+ and v.

An example of β^+ decay is:

$$^{18}F \rightarrow {}^{18}O + \beta^+ + v$$

While the β^- particles, which are equivalent to electrons are found all around in matter as these are constituents of atoms, β^+ particles or positrons are not naturally present in matter. These are "anti-matter" particles which, when met with the corresponding "matter", will annihilate each other, resulting in conversion of matter into energy as per Einstein's mass-energy equation ($E=mc^2$). When a positron is emitted, initially it loses energy as it travels through matter, comes across an electron, and both undergo annihilation, resulting in two photons of 511 keV each travelling in opposite directions.

It may be noted that "positron emission tomography" (PET), a nuclear medicine imaging technique employing radiopharmaceuticals labelled with positron-emitting radionuclide(s), is a highly sensitive imaging technique based on the coincidence counting of the 2 photons emitted at 180°.

4.4 Electron capture (EC)

Radioactive nuclei having fewer neutrons than what is needed for a stable configuration and which do not have adequate energy available to undergo positron β^+ decay, decay by another route named "electron capture", in order to achieve stability. In this mode of decay, an orbital electron is captured and taken into the nucleus, thus facilitating conversion of a proton to a neutron resulting in a nuclide with decrease in atomic number by one. An electron capture reaction can be written as:

$$^{+}p + e^{-} \rightarrow n + v$$

Since there are several orbital electrons (except in the case of elements with very low Z), EC process is a statistical phenomenon, where varied probabilities for EC arise for the K-shell (inner most shell) electrons, L-shell electrons and so on. EC phenomenon results in the depletion of an electron in one of the inner shells of the atom which, in turn, is a vacancy that is filled by one of the outer shell electrons accompanied by emission of characteristic X-rays. Often, the EC mode of decay is accompanied by γ rays and characteristic X-rays as well as Auger electrons that arise due to the interaction of the γ rays and X-rays with the outer orbit electrons.

An example of EC is:

$^{125}I \rightarrow {}^{125}Te$ + 35 keV γ ray (7%) + 27-32 keV Te X-rays (136 %) + ~ 19 (auger electrons)

While positron emission can occur only if at least 1.02 MeV of energy is available from the decay reaction, EC does not need such energy and both modes of decay result in nuclides with an atomic number lower by one. However, when energy is available for β^+ emission, EC may also occur in some cases, while vice versa is not possible. One example is of ^{64}Cu, which decays by β^- emission, β^+ emission as well as EC. It is noteworthy that several factors that influence nuclear stability are responsible in determining the modes of decay and their probabilities.

4.5 Gamma decay (γ)

Gamma rays are electromagnetic rays coming out of a nucleus as a result of the difference in nuclear energy levels of the excited and the ground states of the daughter nuclide when a nuclear transmutation takes place. Most radioactive decays are accompanied by γ rays, although this is not essential. Since γ rays carry the energy arising out of the difference in nuclear energy levels, these are often highly energetic, with energy greater than those of X-rays.

4.6 Isomeric transition (IT)

When an excited nucleus de-excites by emission of a delayed gamma ray, the daughter nucleus is a nuclear isomer of the parent and the process is called isomeric transition.

As mentioned earlier, gamma rays are emitted owing to the energy difference in the nuclear states of the excited and the ground states of the daughter nuclide after a transmutation or decay. Such γ ray emissions are very quick and happen within nanoseconds. However, if the de-excitation of the daughter nuclide from the higher state to ground state does not occur easily (due to rules that govern such transitions – nuclear physics), then such transitions become slow and the excited state of the nuclide is referred to as "metastable" state, indicated by the symbol "m" after the atomic number (e.g. ^{99m}Tc). Nuclear isomers have the same number of protons and the same number of neutrons, only they are arranged in a more stable configuration in the daughter nucleus. The information on physical decay characteristics of medically important radionuclides is listed in Annex 3