BM-3252 MEDICAL PHYSICS

UNIT II

Nuclear Stability and Decay

- Radionuclides are unstable and decay by emission of particle or g-radiation to achieve stable configuration of protons and neutrons in the nucleus.
- The stability of a nuclide in most cases is determined by the N/Z ratio of the nucleus. Thus, whether a nuclide will decay by a particular particle emission or g- ray emission is determined by the N/Z and/or excitation energy of the nucleus.
- Radionuclides can decay by one or more of the six modes:
  - ➢ Spontaneous fission,
  - ➢ Isomeric transition (IT),
  - ➢ Alpha (α) decay,
  - ➢ Beta (β−) decay,
  - ➢ Positron (β +) decay, and
  - ➢ Electron Capture (EC) decay.
- In all decay modes, energy, charge, and mass are conserved.
- The nucleus of an atom consists of neutrons and protons, referred to collectively as nucleons.
- In a popular model of the nucleus (the ―shell model‖), the neutrons and protons reside in specific levels with different binding energies.
- If a vacancy exists at a lower energy level, a neutron or proton in a higher level may fall to fill the vacancy. This transition releases energy and yields a more stablenucleus.
- The amount of energy released is related to the difference in binding energy between the higher and lower levels.
- The binding energy is much greater for neutrons and protons inside the nucleus than for electrons outside the nucleus. Hence, energy released during nuclear transitions is much greater than that released during electron transitions.
- If a nucleus gains stability by transition of a neutron between neutron energy levels, or a proton between proton energy levels, the process is termed an **isomeric transition**.

- In an isomeric transition, the nucleus releases energy without a change in its numberof protons (Z) or neutrons (N).
- The initial and final energy states of the nucleus are said to be isomers. A common form of isomeric transition is gamma decay, in which the energy is released as a packet of energy (a quantum or photon) termed a gamma (γ) ray.
- An isomeric transition that competes with gamma decay is internal conversion, in which an electron from an extra-nuclear shell carries the energy out of the atom.
- It is also possible for a neutron to fall to a lower energy level reserved for protons, in which case the neutron becomes a proton.
- It is also possible for a proton to fall to a lower energy level reserved for neutrons, in which case the proton becomes a neutron. In these situations, referred to collectivelyas beta (β) decay, the Z and N of the nucleus change, and the nucleus transmutes from one element to another.
- In all of the transitions described above, the nucleus loses energy and gains stability. Hence, they are all forms of radioactive decay.
- In any radioactive process the mass number of the decaying (parent) nucleus equals the sum of the mass numbers of the product (progeny) nucleus and the ejectedparticle. That is, mass number A is conserved in radioactive decay.

Spontaneous Emission or Fission

- Fission is a process in which a heavy nucleus breaks into two fragments accompaniedby the emission of two or three neutrons.
- The neutrons carry a mean energy of 1.5 MeV and the process releases about 200MeV energy that appears mostly as heat.
- Spontaneous fission occurs in heavy nuclei, but its probability is low and increases with mass number of the nuclei.
- The half-life for spontaneous fission is $2x10^{17}$ years for ^{235}U and only 55 days for ^{254}Cf. As an alternative to the spontaneous fission, the heavy nuclei can decay by a- particle or g-ray emission.

Isomeric Transition

- A nucleus can exist in different energy or excited states above the ground state, which is considered as the state involving the arrangement of protons and neutrons with the least amount of energy.

•These excited states are called the isomeric states and have lifetimes of fractions of picoseconds to many years.

•When isomeric states are long-lived, they are referred to as metastable states and denoted by ―m‖ as in ^{99m}Tc.

•An excited nucleus decays to a lower energy state by giving off its energy, and such transitions are called isomeric transitions (ITs).

•Several isomeric transitions may occur from intermediate excited states prior to reaching the ground state.

•A parent radionuclide may decay to an upper isomeric state of the product nucleus by a-particle or b-particle emission, in which case the isomeric state returns to the ground state by one or more isomeric transitions.

•Isomeric transition can be described by the following equation:

$$^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + (\text{energy})$$

Gamma ray Emission

•The common mode of an isomeric transition from an upper energy state of a nucleus to a lower energy state is by emission of an electromagnetic radiation, called the γ-ray.

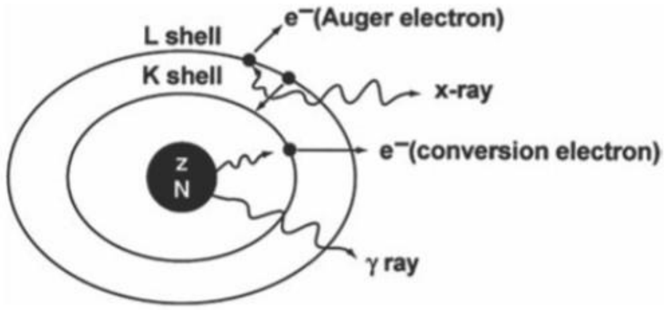
•The energy of the γ -ray emitted is the difference between the two isomeric states.

•For example, a decay of a 525-keV isomeric state to a 210-keV isomeric state will result in the emission of a 315-keV γ -ray.

Internal Conversion

- The excited nucleus transfers the excitation energy to an orbital electron preferably the K-shell electron—of its own atom, which is then ejected from the shell, provided the excitation energy is greater than the binding energy of the electron.
- The ejected electron is called the conversion electron and carries the kinetic energy equal to Eγ – EB, where Eγ is the excitation energy and EB is the binding energy of the electron.

- Even though the K-shell electrons are more likely to be ejected because of the proximity to the nucleus, the electrons from the L shell, M shell, and so forth also may undergo the internal conversion process.



- The ratio of the number of conversion electrons (Ne) to the number of observed γ-radiations (Nγ) is referred to as the conversion coefficient, given as $\alpha = Ne/N\gamma$.
- The conversion coefficients are subscripted as αK, αL, αM . . . depending on which shell the electron is ejected from. The total conversion coefficient αT is then given by $\alpha T = \alpha K + \alpha L + \alpha M + \cdots$

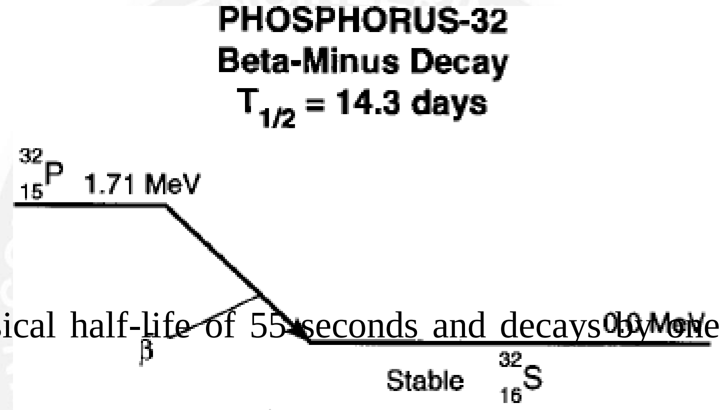
Decay Scheme

- Each radionuclide's decay process is a unique characteristic of that radio nuclide. The majority of the pertinent information about the decay process and its associated radiation can be summarized in a line diagram called a decay scheme.
- Decay schemes identify the parent, daughter, mode of decay, intermediate excited states, energy levels, radiation emissions, and sometimes physical half-life.
- The top horizontal line represents the parent, and the bottom horizontal line represents the daughter.
  - Horizontal lines between those two represent intermediate excited states.
- A diagonal line to the left is used to indicate electron capture decay; a short vertical line followed by a diagonal line to the left indicates either positron or alpha decay; and a diagonal line to the right indicates beta-minus decay.
- Vertical lines indicate gamma ray emission, including isomeric transition.

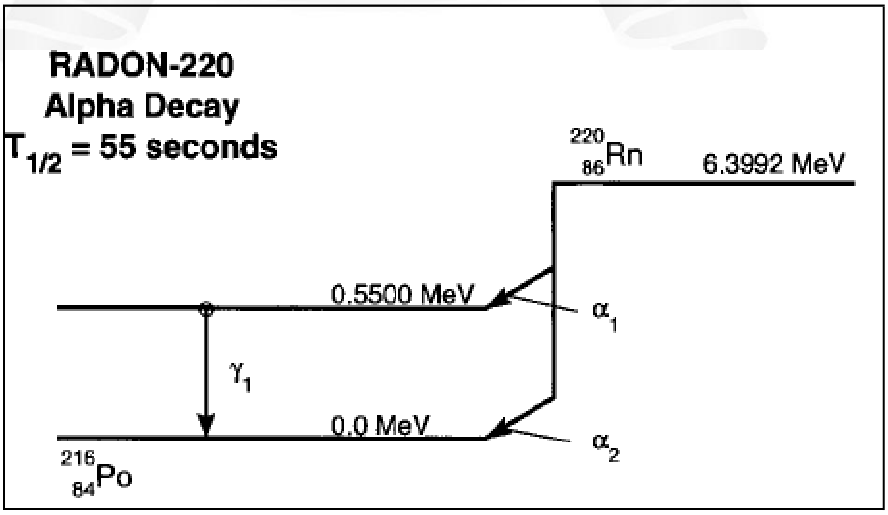
- These diagrams are often accompanied by decay data tables, which provide information on all the significant ionizing radiations emitted from the atom as a result of the nuclear transformation.
- Phosphorus 32 (P-32) is used in nuclear medicine as a therapeutic agent in the treatment of

a variety of diseases, including polycythemia vera, metastatic bone disease, and serous effusions.

- P-32 has a half-life of 14.3 days and decays directly to its ground state by emitting a beta-minus particle with an Emax of 1.71 MeV.
- The average (mean) energy of the beta-minus particle is approximately 1/3 E_{max} (0.6948 MeV), with the antineutrino carrying off the balance of the transition energy.
- There are no excited energy states or other radiation emitted during this decay; therefore, P-32 is referred to as a "pure beta emitter."



- Rn-220 has a physical half-life of 55 seconds and decays by one of two possible alpha transitions.
- Alpha 1 (α1) at 5.747 MeV occurs 0.07% of the time and is followed immediately by a 0.55-MeV gamma ray (γl) to the ground state.
- The emission of alpha 2 (α 2), with an energy of 6.287 MeV; occurs 99.3% of the time and leads directly to the ground state.
- The decay data table lists these radiations together with the daughter atom, which



hasa -2 charge and a small amount of kinetic energy as a result of alpha particle emission.