Radioactivity

By: Ulfat Hussain
V. Lecturer
University of Sargodha
(Sub Campus Bhakkar)

Nuclear Radioactivity & Stability

- **Nuclear Radioactivity** (also known as Radioactive or nuclear decay, radioactive or nuclear disintegration) is the **phenomenon** by which an unstable nucleus loses energy by spontaneously emitting some kind of radiation

- If nucleus is stable i.e. it doesn't spontaneously emit any kind of radiation, it is called non- radioactive and this phenomenon is known as Nuclear stability

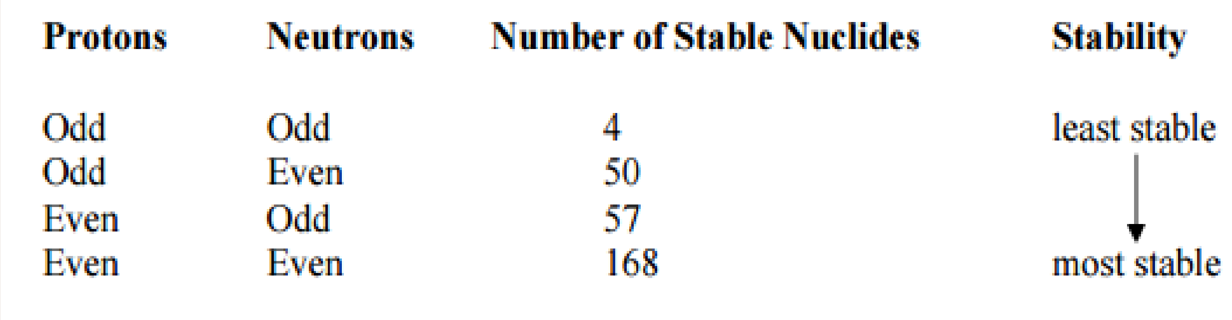
- **Stable nucleus – non-radioactive**
- **Unstable nucleus– radioactive**

- Keep in mind that less stable means more radioactive and more stable means less radioactive.

What makes the nucleus a stable one?

- There are no concrete theories to explain this, but there are only general observations based on the available stable isotopes.
- It appears that neutron to proton (n/p) ratio is the dominant factor in nuclear stability.
- This ratio is close to 1 for atoms of elements with low atomic number and increases as the atomic number increases.
- Then how do we predict the nuclear stability?
- One of the simplest ways of predicting the nuclear stability is based on whether nucleus contains odd/even number of protons and neutrons:

- **Nuclides containing odd numbers of both protons and neutrons are the least stable means more radioactive.**
- **Nuclides containing even numbers of both protons and neutrons are most stable means less radioactive.**
- **Nuclides contain odd numbers of protons and even numbers of neutrons are less stable than nuclides containing even numbers of protons and odd numbers of neutrons.**
- **In general, nuclear stability is greater for nuclides containing even numbers of protons and neutrons or both.**



Protons	Neutrons	Number of Stable Nuclides	Stability
Odd	Odd	4	least stable
Odd	Even	50	↓
Even	Odd	57	
Even	Even	168	most stable

Examples

- **Based on the even-odd rule presented above, predict which one would you expect to be radioactive in each pair?**
- (a) ${}^{16}_{8}O$ and ${}^{17}_{8}O$
- (b) ${}^{35}_{17}Cl$ and ${}^{36}_{17}Cl$
- (c) ${}^{20}_{10}Ne$ and ${}^{17}_{10}Ne$
- (d) ${}^{40}_{20}Ca$ and ${}^{45}_{20}Ca$
- (e) ${}^{195}_{80}Hg$ and ${}^{196}_{80}Hg$

Answer

(a) The $^{16}{}_{8}O$ contains 8 protons and 8 neutrons (even-even) and the $^{17}{}_{8}O$ contains 8 protons and 9 neutrons (even-odd). Therefore, $^{17}{}_{8}O$ is radioactive.

(b) The $^{35}{}_{17}Cl$ has 17 protons and 18 neutrons (odd-even) and the $^{36}{}_{17}Cl$ has 17 protons and 19 neutrons (odd-odd). Hence, $^{36}{}_{17}Cl$ is radioactive.

(c) The $^{20}{}_{10}Ne$ contains 10 protons and 10 neutrons (even-even) and the $^{17}{}_{10}Ne$ contains 10 protons and 7 neutrons (even-odd). Therefore, $^{17}{}_{10}Ne$ is radioactive.

(d) The $^{40}{}_{20}Ca$ has even-even situation and $^{45}{}_{20}Ca$ has even-odd situation. Thus, $^{45}{}_{20}Ca$ is radioactive.

(d) The $^{195}{}_{80}Hg$ has even number of protons and odd number of neutrons and the $^{196}{}_{80}$ Hg has even number of protons and even number of neutrons. Therefore, $^{195}{}_{80}Hg$ is radioactive.

Discovery of Radioactivity

Henri Bequerel (1852-1908) was using naturally fluorescent minerals to study the properties of x-rays (1896), he found a mineral (uranium) would darken a photographic plate even if the plate was wrapped while X-rays needed an external stimulus .

- He found that mineral spontaneously emitted a new kind of radiation which later named as radioactivity

Discovery of Radioactivity

Though it was Henri Becquerel that discovered radioactivity, it was Marie Curie who coined the term.
Marie (1867-1934) and Pierre (1859-1906) Curie isolated two previously unknown radioactive materials, polonium and radium

- Radioactivity was found to be unaffected by chemical and physical testing, showing that the radiation came from the atom itself – specifically from the disintegration or decay of an unstable nucleus

Discovery of Radioactivity

- 1898 – Ernest Rutherford began studying the nature of the rays that were emitted
- Classified into three distinct types according to their penetrating power.
- Alpha decay (α) – positively charged;can barely penetrate a piece of paper
- Beta Decay (β) – negatively charged; pass through as much as 3mm of aluminium
- Gamma Decay (γ) – neutral; Extremely penetrating

Types of Radiation

- Alpha Rays (or Alpha particles) = nuclei of Helium atoms (2 protons, 2 neutrons)
- Beta Rays = electrons (created within the nucleus)
- Gamma Rays = high-energy photons (packets of energy)

Alpha Decay

- The loss of 2 neutrons & 2 protons (Helium nucleus) changes the atom.

$$^{226}_{88}Ra \longrightarrow ^{222}_{86}Rn + ^{4}_{2}He$$

Parent nucleus

Daughter nucleus

A Radium-226 atom decays into a Radon-222 atom and a Helium nucleus

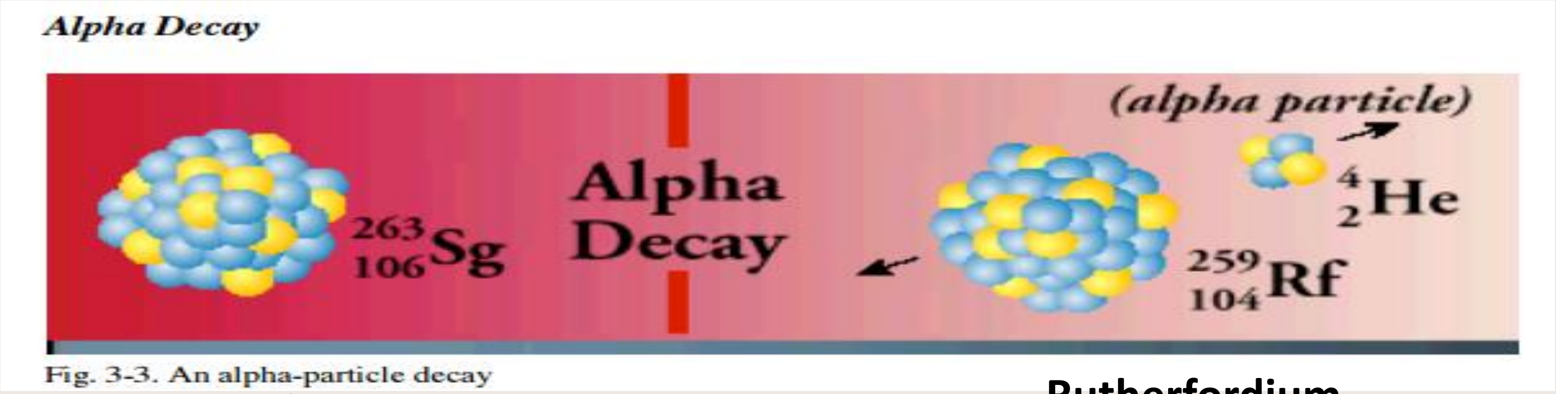


Fig. 3-3. An alpha-particle decay

Seaborgium

Rutherfordium

Alpha Decay

- Occurs because the strong nuclear force is unable to hold very large nuclei together.

- The electrical repulsion between the protons of the nucleus pushes apart and can act over much larger distance then the strong nuclear force.

- Since the strong nuclear force can only act on particles directly beside each other, the electrical repulsion overpowers the strong nuclear force and pushes the nucleons apart.

Beta Decay

- Beta decay occurs with the emission of an electron (e^-) or β^- particle.

$$^{14}_{6}C \longrightarrow ^{14}_{7}N + \bar{e} + a\ neutrino$$

The total number of nucleons are the same in the daughter nucleus as in the parent nucleus.

With the loss of an electron, the nucleus must have an extra positive charge, so in this case the number of protons is 7, which is Nitrogen.

Beta Decay

- The electron emitted in beta decay is NOT an orbital electron; the electron is created in the nucleus itself.
- One of the neutrons changes to a proton and in the process (to conserve charge) throws off an electron.
- These particles are referred to as “beta particles” so as not to confuse them with orbital electrons.

Beta Decay and the neutrino

- Through experimentation, scientists found that some of the fundamental principles of physics did not hold true (Law of Conservation of Energy and Law of Conservation of Momentum (both linear and angular).
- 1930 – Wolfgang Pauli proposed that there was a new particle that was very difficult to detect was emitted in beta decay, as well as the electron.
- This new particle was named “neutrino” (little neutral one) by Enrico Fermi (1934)

Beta Decay and the neutrino

- In 1956, complex experiments produced further evidence for the neutrino, but by then physicists had already accepted its existence.
- The symbol for the neutrino is the Greek letter “nu” (ν)
- So, the equation from earlier becomes

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + \bar{e} + \bar{\nu}$$

Negatron Decay

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + \overset{-}{e} + \bar{\nu}$$

The bar over the neutrino means that it is an *antineutrino*.

This type of decay is also called beta negative, or negatron decay.

Negatron decay occurs when the isotope lies above the stable isotope line; there are too many neutrons compared to the number of protons.

Positron Decay

$$^{18}_{9}F \longrightarrow {}^{18}_{8}O + \overset{+}{e} + \overset{+}{\nu}$$

- Positron decay occurs when there are too few neutrons compared to the number of protons. These isotopes lie below the stable isotope line.
- In this type of beta decay, the particle that is emitted is called a positron, as it has the same mass as an electron, but has a charge of +1 (also written as $\overset{+}{e}$ or β^{+})
- The positron is called the antiparticle to the electron.

Beta Decay

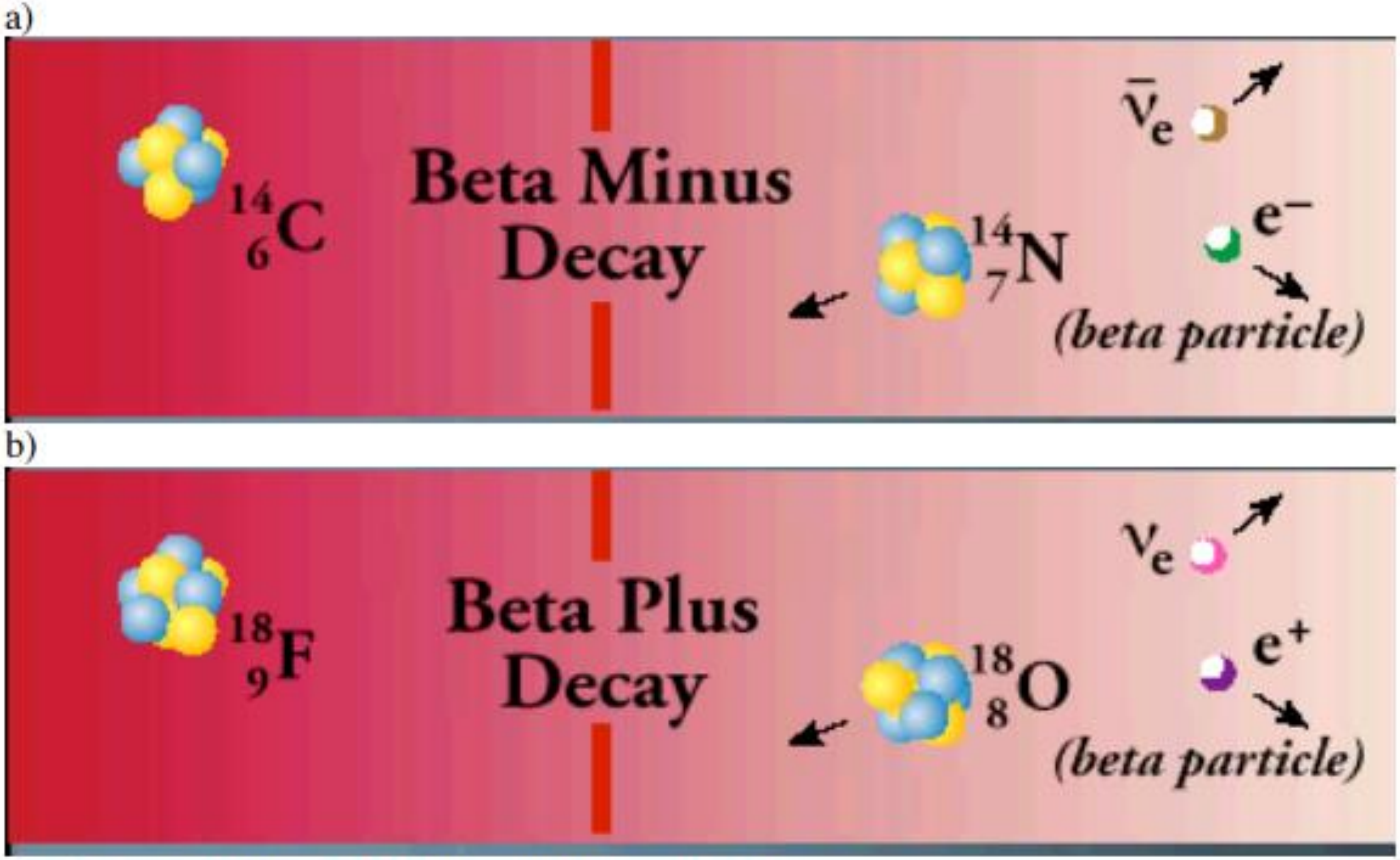
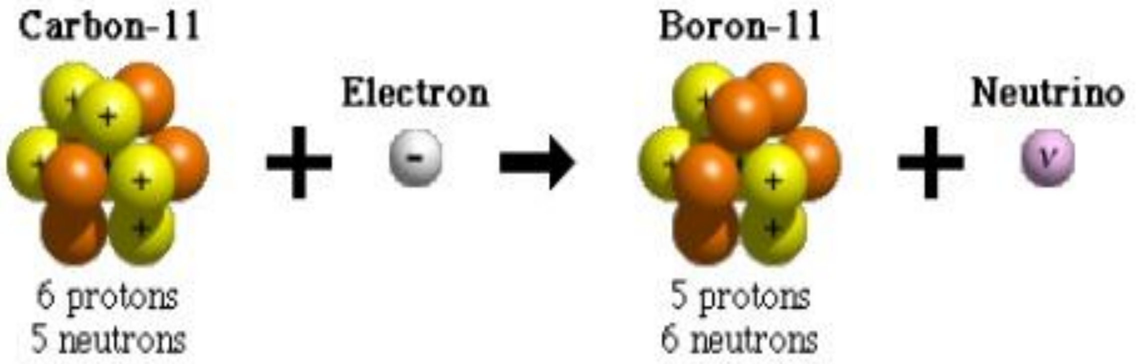


Fig. 3-5. Beta decays. a) Beta-minus decay. b) Beta-plus decay.

Electron Capture (EC)

- **Electron capture** *(EC)* – is a process in which a nucleus absorbs an electron from an inner electron shell, usually the first or the second. Once inside the nucleus, the captured electron combines with a proton to form a neutron.

$$ {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{1}_{0}\mathrm{n} $$



Beta Decay and the weak force

- In beta decay, it is the weak nuclear force that plays the crucial role.
- The neutrino interacts with matter only via the weak force, which is why it is so hard to detect.

Gamma Decay

Gamma rays are photons having very high energies.

The decay of a nucleus by the emission of a gamma ray is much like the emission of photons by excited electrons.

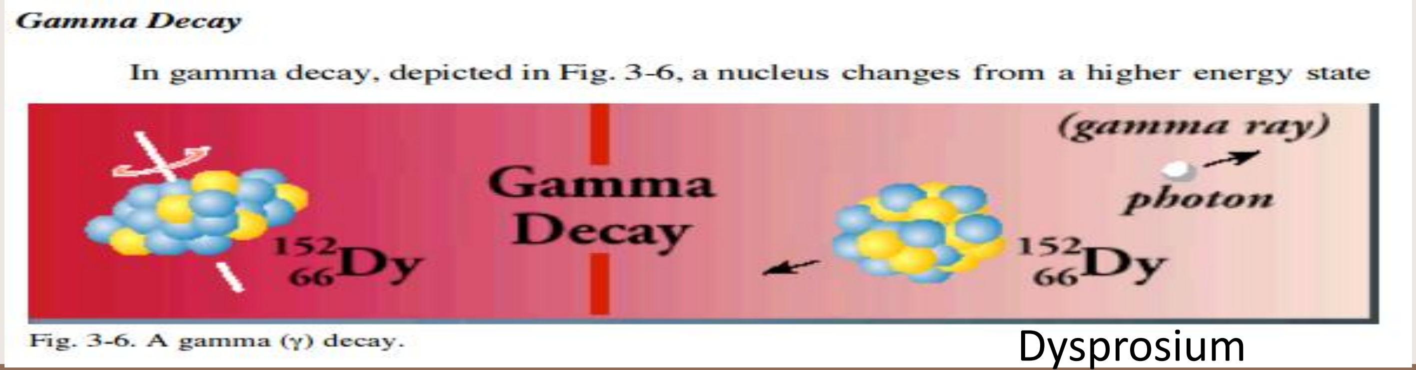
- The gamma rays come from an excited nucleus that is trying to get back to its ground state.
- The nucleus could be in an excited state either from a collision with another particle or because it is a nucleus left over from a previous radioactive decay.

Gamma Decay

$$^{12}_{6}C \rightarrow {}^{12}_{6}C + \gamma$$

A nucleus may remain in an excited state for some time before it emits a gamma ray. The nucleus is then said to be in a metastable state and is called an isomer.

The nucleus can also return to its ground state by a process called internal conversion, where no gamma ray is emitted. The nucleus interacts with an electron and loses its energy in that way. The electron then loses the energy as an x-ray. X-rays come from atom-electron interactions, while gamma rays come from nuclear processes.



Gamma Decay

In gamma decay, depicted in Fig. 3-6, a nucleus changes from a higher energy state

Fig. 3-6. A gamma (γ) decay.

Conservation of Nucleon Number

- The following laws all hold true:
  - Law of Conservation of Energy
  - Law of Conservation of Linear Momentum
  - Law of Conservation of Angular Momentum
  - Conservation of Electric Charge
  - Law of Conservation of Nucleon Number
- The total number of nucleons stays the same in any decay, but the different types can change (protons into neutrons and vice versa).

Half Life and Rate of Decay

- Radioactivity is a random event; we do not know which atom will decay at what time, but can use probability and statistics to tell us how many of the atoms will decay in a certain time period.
- The equation used to determine how much will decay in that time period is:

$$\Delta N = -\lambda N \Delta t$$

Half Life and Rate of Decay

Number of Decays that occur in the time period

Number of radioactive Nuclei present

$$N = -\lambda N_o \Delta t$$

Greek Letter “Lambda” – decay constant

The decay constant is different for different isotopes; the greater the decay constant, the more radioactive the isotope is.

Time period (in seconds)

Radioactive Decay Law

- The previous equation can be rearranged to find the number of atoms left after a specified amount of time to decay.

$$N = N_o e^{-\lambda t}$$

- The number of decays per second is called the **activity** of the sample.
- To signify how fast an isotope decays, the term **“half life”** is used. The half life of an isotope is the time it takes half of the original sample to decay

Half Life

- The time which is spent so that the number of radioactive atoms reduce to half
- When t=τ , N=N_0/2 ,so

$$\frac{N_0}{2} = N_0 \exp(-\lambda\tau)$$

$$1/2 = \exp(-\lambda\tau)$$

$$\ln(1/2) = -\lambda\tau$$

$$\ln 1 - \ln 2 = -\lambda\tau$$

$$\ln 2 = \lambda\tau$$

$$\tau = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

- Every radioactive substances has its own λ and τ

Half Life

- The half lives of known radioactive isotopes vary from about 10^{-22} seconds to 10^{28} seconds (about 10^{21} years) Most tables and charts show half life as $T_{1/2}$
- The half life and decay constant have an inverse relationship to one another; the longer the half life, the lower the decay constant (the more slowly it decays) and vice versa .
  The precise relationship is

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Decay Series

- It is often the case that one radioactive substance decays into another radioactive substance and so on.
- These successive decays are called a **decay series**.
- Because of such decay series, certain radioactive elements are found in nature that otherwise would not be.

Radioactive Dating

The age of any once-living object can be determined using the natural radioactivity of carbon-14.
All living plants and animals absorb CO_2 from the air and use it to synthesize organic molecules.

Most of these atoms are carbon-12, but a small amount are carbon-14. Neutrons in cosmic radiation collide with nitrogen in the atmosphere and change it into carbon-14 .
Carbon-14 has a half life of 5730 years.

.

Radioactive Dating

- As long as a plant is alive, it continually absorbs CO_2 from the air to build new tissue or replace old. Animals continuously eat plant matter, so they receive a fresh supply of carbon for their tissues. Once the organism dies, there is no longer a fresh supply of carbon-14, and the amount of carbon-14 begins to decline due to radioactive decay.
- It is the ratio of carbon-12 to carbon-14 atoms that determines the age of the object.
- Objects older than 60,000 years are difficult to determine due to the small amount of carbon-14 present.

Geologic Dating

- Radioactive isotopes with longer half lives can be used to determine the age of older materials.
- Uranium-238 is used to determine the age of rocks due to its half life of 4.5×10^{9} years.
- Using these dating techniques, scientists have come up with a geologic timeline.

Detecting Radiation

Radioactive particles are far too small to be detected by our senses; it is for this reason that scientists have created a variety of ways to detect the alpha, beta, and gamma decays of nuclei such as.

1. Gas detectors
2. Scintillation detectors
3. Semiconductor detector