Origin of α-, β- and γ-rays

α-, β- and γ-rays are producted by nuclear decay.

(1) Emission of α-rays: When an α-particle emits from the nucleus, atomic number and mass number of an element decreases by 2 and 4 units respectively.

$$^{213}_{83}\text{Bi} \longrightarrow {}^{209}_{81}\text{Tl} + \underset{\alpha\text{-particle}}{^{4}_{2}\text{He}}$$

An α-particle is composed of two protons and two neutrons.

$$2\,{}_{1}^{1}p + 2\,{}_{0}^{1}n \longrightarrow {}_{2}^{4}He$$

Thus atomic number and mass number of an element decreases by 2 and 4 units respectively of an element.

(2) Emission of β-rays: β-particles are nuclear electrons. When a β-particles emits from the nucleus, mass number of an element does not change but the atomic number is increased by one unit.

$${}_{83}^{213}Bi \longrightarrow {}_{84}^{213}Po + \underset{\beta\text{-particle}}{{}_{-1}^{0}e}$$

It is considered that, when one neutron decays, one electron (β-particle), one proton and antinutrino is produced.

$$\underset{\text{Neutron}}{{}_{0}^{1}n} \longrightarrow \underset{\text{Proton}}{{}_{1}^{1}p} + \underset{\beta\text{-particle}}{{}_{-1}^{0}n} + \underset{\text{Antinutrino}}{\bar{\nu}}$$

Thus due to emission of β-particle, atomic number of an element increases by one unit but mass number remains as such.

(3) Emission of γ-rays: γ-rays are electromagnetic radiations like x-rays. γ-rays are produced from nucleus during nucleus decay. After emission of α- or β-particles, the element is in excited state. The element in the excited state emits γ-radiations and comes to the ground state. There is no effect of γ-emission on atomic number and mass number of an element.

Group Displacement Law

Soddy, Fajans and Russell (1911–1913) observed that when an α-particle is lost (called α-decay), a new element with atomic number less by 2 and mass number less by 4 is formed. Similarly, when β-particle is lost (called α-decay), a new element with atomic number greater by 1 is obtained. The element emitting the α or β particle is called *parent element* and the new element formed is called *daughter element.* The above results have been summarized as **'Group Displacement Laws'** as follows:

(i) When an α-particle is emitted the new element formed is displaced two positions to the left in the periodic table than that of the parent element (because the atomic number decreases by 2).

For example, when ${}_{92}^{238}U$ nucleus emits an α-particle, thorium nucleus ${}_{90}^{234}Th$ is obtained.

$${}_{92}^{238}U \longrightarrow {}_{90}^{234}Th + {}_{2}^{4}He \qquad \ldots(1)$$

(ii) When a β-particle is emitted, the new element formed is displaced one position to the right in the periodic table than that of the parent element (because atomic number increases by 1).

For example, the emission of β-particle by ${}_{90}^{234}Th$ and ${}_{6}^{14}C$ may be represented as follows:

$${}_{90}^{234}Th \longrightarrow {}_{91}^{234}Pa + {}_{-1}^{0}e \qquad \ldots(2)$$

$${}_{6}^{14}C \longrightarrow {}_{7}^{14}N + {}_{-1}^{0}e \qquad \ldots(3)$$

Chemical equations such as (1),(2) and (3) representing nuclear changes are called **nuclear reactions.**

Explanation: The results of the group displacement laws may be explained as follows:

Since an α-particle is simply a helium nucleus (containing two protons and two neutrons), therefore, loss of α-particle means loss of two protons and two neutrons. Thus the new element formed has atomic number less by 2 and mass number less by 4.

It is believed that for the emission of β-particle to occur, a neutron changes to a proton and an electron *i.e.*,

$$\text{Neutron} \longrightarrow \text{Proton} + \text{Electron } (\beta\text{-particle})$$

As a result, the number of protons in the nucleus increases by 1 and so does the atomic number.

Increase or decrease in the number of protons in the nucleus (due to loss of α or β particle) is accompanied simultaneously by the loss or gain of electrons in the extranuclear part (from the surroundings) so that the electrical neutrality is maintained in the new atom formed.

Further, it is important to mention here that in addition to α, β and γ emissions, two more decay processes that have been observed are positron (β^+) emission and K-electron capture. These are briefly explained below:

(i) Positron (β^+) emission: A positron is a positively charged β-particle, represented by β^+ or ${}^{0}_{+1}e$. The emission of a positron, therefore, results in the decrease of atomic number by one unit. It is believed-that the positron emission takes place due to change of a proton into a neutron in the nucleus

$$\text{Proton} \longrightarrow \text{Neutron} + \beta^+ \text{ or } {}^{0}_{+1}e \quad \text{(positron)}$$

i.e.,

$$P^+ \longrightarrow n + \beta^+$$

An example of a reaction involving β^+ emission is $\quad {}^{13}_{7}N \longrightarrow {}^{13}_{6}C + \beta^+ \left(\text{or } {}^{0}_{+1}e\right)$

(ii) K-electron capture: In certain nuclides, the nucleus captures an electron from the K-shell (being nearest to the nucleus). The vacancy created is filled up with the electron from the higher shells (thereby emitting X-rays). A result of K-electron capture, a proton in the nucleus is converted into a neutron $\left(p^+ + e^- \longrightarrow n\right)$. Hence atomic number decreases by one unit. An example of a reaction involving K-capture is given below:

$${}^{133}_{56}Ba + {}^{0}_{-1}e \longrightarrow {}^{133}_{55}Cs + X-\text{rays}$$

Summary:

$${}^{A}_{Z}X \xrightarrow{-\alpha\text{ particle}} {}^{A-4}_{Z-2}Y$$

$${}^{A}_{Z}X \xrightarrow{-\beta\text{particle}} {}^{A}_{Z+1}Y$$

$${}^{A}_{Z}X \xrightarrow{-\beta^+\text{(positron)}} {}^{A}_{Z-1}Y$$

$${}^{A}_{Z}X \xrightarrow[\text{(K-capture)}]{+e^-} {}^{A}_{Z-1}Y$$

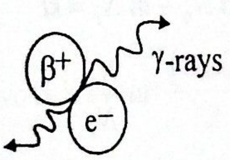
Emission of neutrino and antineutrino: On the basis of law of conservation of mass and energy, it has been postulated that when a β^--particle is emitted, it is accompanied by the emission of chargeless, massless particle, called **neutrino** e.g.,

$${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \underset{\text{(neutrino)}}{\nu}$$

Similarly, when a positron emission takes place, it is accompanied by emission of a chargeless, massless particle called antineutrino (which is identical to the neutrino but has opposite spin) e.g.,

$${}^{15}_{8}O \longrightarrow {}^{15}_{7}N + {}^{0}_{+1}e + \underset{\text{(antineutrino)}}{\overline{\nu}}$$

Annihilation of a positron and an electron: Positron was the first antiparticle to be discovered. It is similar to the electron in all respects except charge. When a positron and an electron collide, they annihilate each other γ-radiation equivalent to the masses of the two particles is produced.



Why is electron capture accompanied by production of X-rays? The capture of the orbital electron leaves a vacancy in the K or L-shell and when an outer electron falls into this vacancy, X-rays emission follows.

Radioactive Disintegration

Spontaneous disintegration of a nucleus is called radioactive disintegration or decay.

Examples:

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

$${}^{238}_{92}U \xrightarrow{\text{disintegration}} {}^{234}_{90}Th + {}^{4}_{2}He$$

$${}^{234}_{90}Th \xrightarrow{\text{disintegration}} {}^{234}_{91}Pa + \underset{\beta\text{-particle}}{{}^{0}_{-1}e}$$

$$^{213}_{83}\text{Bi} \xrightarrow{\text{disintegration}} {}^{213}_{84}\text{Po} + \underset{\beta\text{-particle}}{{}^{0}_{-1}e}$$

Rate of Radioactive Disintegration or Decay:

Radioactive substances spontaneously disintegrated regularly. Rate of disintegration decreases with increase in time. The rate of disintegration depends only upon the nature of radioactive substance and is independent of the external conditions such as pressure, temperature catalyst etc. Radioactive decay follows first order kinetics. Suppose a radioactive element A decays to form an element B.

$$A \longrightarrow B$$

Initial number of element $\quad N_t \quad N_0$

Number of elements after time t

The rate of disintegration at time t is given by $\quad -\frac{dN_t}{dt} \propto N_t$

Or, $\quad -\frac{dN_t}{dt} = kN_t$

where k is the disintegration constant or decay constant.

Or, $\quad -\frac{dN_t}{N_t} = kdt \quad \ldots(1)$

If $dt = 1$ sec, then $\quad k = -\frac{dN_t}{N_t} \quad \ldots(2)$

Thus disintegration constant may be defined as the fraction of the total no. of atoms of a substance present any time which disintegrates in one second.

Integrating equation (1)

$$-\int \frac{dN_t}{N_t} = k\int dt$$

$$-\ln N_t = kt + C \quad \ldots(3)$$

Or,

where C is the integration constant.

when $t = 0$, $\quad N_t = N_0$

Putting these values in equation (3)

$$-\ln N_0 = C$$

Now put the values of C in equation (3)

$$-\ln N_t = kt - \ln N_0 \quad \ldots(4)$$

Or, $\quad \ln N_0 - \ln N_t = kt$

Or, $\quad \ln \frac{N_0}{N_t} = kt \quad \ldots(5)$

Or, $\quad k = \frac{1}{t} \ln \frac{N_0}{N_1} \quad \ldots(6)$

Or, $\quad \boxed{k = \frac{2.303}{t} \log \frac{N_0}{N_t}} \quad \ldots(7)$

$$(\because \ln x = 2.303 \log x)$$

Equation (7) can also be written as

$$k = \frac{2.303}{t} \log \frac{a}{a-x} \quad \ldots(8)$$

Where,

a = Initial amount of radioactive substance.

$a - x$ = Amount of radioactive substance present at time t.

x = Amount of radioactive substance disintegrated.

Equation (6) can also be written as

$$\frac{N_0}{N_t} = e^{kt} \quad \text{...(9)}$$

Or

$$\frac{N_t}{N_0} = e^{-kt}$$

Or

$$\boxed{N_t = N_0 e^{-kt}} \quad \text{...(10)}$$