Chapter "4"

Alpha Decay

Until the discovery of spontaneous fission , α – **decay** was the only known type of radioactive disintegration , in which nuclei emits heavy charged particles ($^4_2He_2$) , i.e. α – **particle** is the **nucleus** of the Helium atom . Alpha particle is a very **stable** and tightly bound structure . Alpha emission is a coulomb repulsion effect , it becomes increasingly important for heavy nuclei because the disruptive coulomb force increases as (Z^2) faster than the nuclear binding force (**which increases approximately as A**) . Most nuclei with $A > 190$ and (many with $150 < A < 190$) are energetically can decay by α – **emission** . In α - **decay** the nuclear reaction can be written in this form **:**

$$^A_ZX_N \xrightarrow{\alpha\text{ - decay}} {}^{A-4}_{Z-2}Y_{N-2} + {}^4_2He_2$$

All the α - **ray** emitted by heavy nuclei ($A > 190$) can be classified into one of the **four** independent decay chains with mass numbers **4n , 4n + 1 , 4n + 2** , where (**n**) is an integer . The decay process will tend to concentrate the nuclei in the longest – lived member of the chain.

① **The Thorium (4n) chain :**

Every member of this chain has a mass number which is a multiple of **four** , i.e. $A = 4n$. The longest – lived member $^{232}_{90}Th$ has a half – life , $T_{1/2} = 1.41 \times 10^{10}$ **year** $= 14.1 \times 10^9$ **year** , which is about **Three times** the age of the earth ($T_{earth} = 4.5 \times 10^9$ **year**).

② **The Neptunium (4n + 1) chain :**

In nature there is no $A = 4n + 1$ series , This is because its longest lived member $^{237}_{93}Np$ has a half – life of only 2.14×10^6 **year** . This series can be produced artificially .The ($4n + 1$) series terminates at an stable $^{209}_{83}Bi$, this is the only series which do not terminate at an isotope of **Pb**.

③ **The Uranium (4n + 2) chain :**

This is the longest known series. In nature it begins with the heaviest naturally occurring nucleus $^{238}_{92}U$ ($T_{1/2} = 4.47 \times 10^9$ **year**) , which is the age of the earth.

④ The Actinium (4n + 3) chain :

This is the only naturally occurring nuclei which **undergoes fission** by **slow** neutrons . **Actinium** $^{227}_{89}\mathbf{Ac}$ can be separated from **Uranium** minerals . The **β – ray** spectrum of **actinium** has a maximum energy of only **0.04 MeV** . **Actinium** can be produced artificially in reactors by irradiator of $^{226}_{88}\mathbf{Ra}$, the nuclear reaction is **:**

$$^{226}_{88}\mathbf{Ra} + {}^{1}_{0}\mathbf{n} \longrightarrow {}^{226}_{88}\mathbf{Ra}^{*} \xrightarrow{\beta^-} {}^{227}_{89}\mathbf{Ac}$$

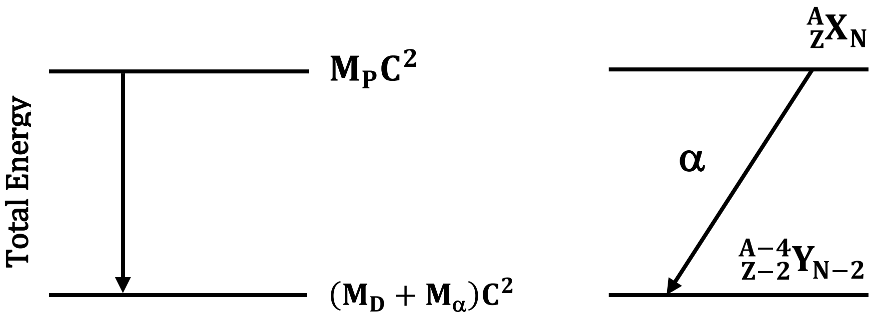
Fissionable materials $^{235}\mathbf{U}$ and $^{239}\mathbf{Pu}$ are belong to this series.

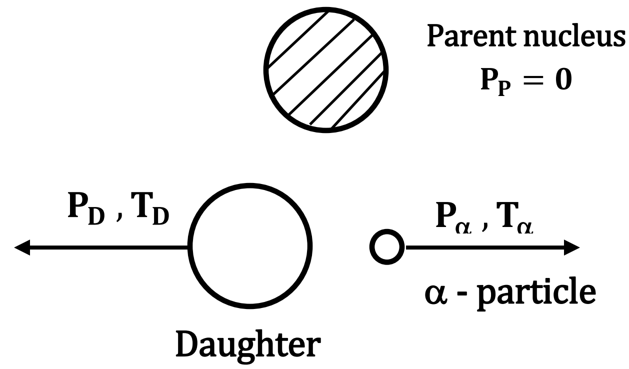
Table : Some characteristics of the Disintegration series of the Heavy Elements

Name of series	Type	Final Nucleus (Stable)	Longest Lives Member	
			Nucleus	Half – life (years)
Thorium	4n	^{208}Pb	^{232}Th	14.1×10^9
Neptunium	4n + 1	^{209}Bi	^{237}Np	2.14×10^6
Uranium	4n + 2	^{206}Pb	^{238}U	4.47×10^9
Actinium	4n + 3	^{207}Pb	^{235}U	7.04×10^8

Energetics of α - decay :

The spontaneous emission of **α - particle** can be represented as follows :





Energy Diagram **Momentum Diagram**

In **α - decay** we assume the initial decaying nucleus (**parent nucleus**) to be at rest ($T_P = 0$, $P_P = 0$) , then the energy of the initial system is just the <u>**rest**</u> energy of the parent nucleus $M_P C^2$. The final state (**after decay**) consist of daughter and **α - particle** , from the conservation of **energy** and **momentum** we have :

$$M_P C^2 = M_D C^2 + T_D + M_\alpha C^2 + T_\alpha \quad \text{-----------} \; ①$$

$$0 = \vec{P}_D + \vec{P}_\alpha \quad \text{-----------} \; ②$$

Where T_α and $\vec{P}_\alpha$ are the kinetic energy and momentum of **α - particle**

T_D and $\vec{P}_D$ are the kinetic energy and momentum of **daughter nucleus**

$$\therefore \; M_P C^2 = (M_D + M_\alpha)C^2 + (T_D + T_\alpha) \quad \text{-----------} \; ③$$

The decay energy is the net energy released in the decay called the **Q – value** is the <u>**sum**</u> of the resultant <u>**kinetic**</u> energies , i.e.

$$Q = T_D + T_\alpha \quad \text{-----------} \; ④$$

Therefore $M_P C^2 = (M_D + M_\alpha)C^2 + Q$

$$\therefore \; Q = [M_P - (M_D + M_\alpha)]C^2 \quad \text{-----------} \; ⑤$$

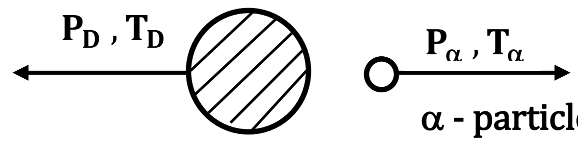
$$Q_\alpha = (M_P - M_D + M_\alpha)C^2 \quad \text{-----------} \; ⑥$$

And the decay occurs spontaneously if **Q > 0** , the **Q – value** can be calculated from atomic masses given in tables (**in amu**) then multiplying by **931.5** (**1 amu = 931.5 MeV**) to have the **Q – value** in **MeV.**

Since the **Q – value** is given by **eq.** ④ , $\mathbf{Q = T_D + T_\alpha}$ and since the kinetic energy $\mathbf{T \ll mc^2}$,we can safely use nonrelativistic expressions to evaluate $\mathbf{T_D}$ and $\mathbf{T_\alpha}$.
From **eq.** ② we have $\mathbf{P_D = -P_\alpha}$

$$\mathbf{T_D = \frac{P_D^2}{2M_D} = \frac{P_\alpha^2}{2M_D} = \frac{\cancel{2}\, M_\alpha T_\alpha}{\cancel{2}\, M_D} = \frac{M_\alpha}{M_D} T_\alpha}$$

$$\therefore\ \mathbf{T_D = \frac{M_\alpha}{M_D} T_\alpha} \quad \text{-----------} \ ⑦$$



The recoil kinetic energy of daughter $\mathbf{T_D}$ is <u>**not**</u> negligible as it is in the case of **γ – decay** because **α - particle** is a large mass.

$\mathbf{Q_\alpha}$ طاقة انحلال الفا

$\mathbf{T_\alpha}$ طاقة حركية لألفا

Since $$\mathbf{Q_\alpha = T_D + T_\alpha = \frac{M_\alpha}{M_D} T_\alpha + T_\alpha = \frac{M_D + M_\alpha}{M_D} T_\alpha}$$

$$\mathbf{Q_\alpha = \frac{M_P}{M_D} T_\alpha = \left(\frac{M_P}{M_P - 4}\right) T_\alpha}$$

and since $\mathbf{M_P \approx A}$; (**A** is the **mass number of parent nucleus**)

$$\therefore\ \mathbf{Q_\alpha \cong \left(\frac{A}{A-4}\right) T_\alpha} \quad \text{-----------} \ ⑧$$

or $$\mathbf{T_\alpha = Q_\alpha \left(\frac{A}{A-4}\right) = Q_\alpha \left(1 - \frac{4}{A}\right)}$$

$$\mathbf{T_\alpha = Q_\alpha \left(1 - \frac{4}{A}\right)} \quad \text{-----------} \ ⑨$$

Alpha decay cannot take place unless $\mathbf{Q_\alpha > 0}$, i.e. is positive and the separation energy of **α - particle** $\boldsymbol{S_\alpha}$ is equal to **:**

$$\mathbf{Q_\alpha = -\,\boldsymbol{S_\alpha}}$$

$$\mathbf{Q_\alpha = B_{tot.}\left({}^{A-4}_{Z-2}X_{N-2}\right) + B_{tot.}(\alpha) - B_{tot.}\left({}^{A}_{Z}X_{N}\right)}$$