α - Decay

Alpha - Emission

Alpha emission :- The nucleus consist of protons and neutrons collectively known as nucleons. The number of proton is equal to the atomic number Z and the number of neutrons is equal to $(A-Z)$ where A is the mass number. The protons carry a positive charge and there is an electrostatic force of repulsion between them. The total repulsive force in the nucleus is approximately proportional to Z^2. The gravitational force of attraction between the nucleons is very weak. The nuclear attractive force between the nucleons is of a very short range and the total binding energy of a nucleus is therefore approximately proportional to its mass number. A.

High energy of α-particles favours emission :-

The α-particles which consist of two protons and two neutrons has a very high binding energy of more than 28 MeV because the α-particle mass is sufficiently smaller than that of its constituent nucleons.

Thus the formation of an α-particle within the nucleus makes available the kinetic energy of the particle must have to escape from the nucleus. The K.E is known as disintegration energy released in the process of emission of a particle from a heavy nucleus is given by

$$Q = [M_p - (M_d + M_2)]C^2 \quad \text{---} (1)$$

where M_p is the mass of the parent nucleus, M_d the mass of the daughter of nucleus, and M_2 the mass of the particle emitted. Nuclei which contain 210 or more nucleons are so large that the short range molecular forces that hold them together are hardly able to counterbalance the mutual repulsive force between the protons. The α-decay occur in such a nuclei as a means of increasing their stability by reducing their size and is energitically possible. The α-decay from U^{238}_{92} nucleus is accompanied by a release of 5.4 MeV of energy. This value agree with the values predicted from the nuclear masses involved in the process.

The radio active nuclei whose atomic number Z is greater than 82 (mass number 208) spontaneously disintegrate with parent nucleus decaying into a daughter nucleus have a kinetic energy even if the ~~kinetic energy~~ parent nucleus is at rest, the condition necessary for emission of an α - particle is that the sum of the masses of the daughter nucleus and the α - particle must be less than the mass of the parent nucleus. The decrease in mass appears as the kinetic energy of the α - particle and the daughter nucleus.

proton and $_2He^3$ emission not possible:- On the other hand release of proton will require 6.1 MeV and that of $_2He^3$ nucleus 9.6 MeV of energy to be supplied from outside. Hence emission of individual proton or $_2He^3$ nuclei is not energetically possible.

Condition for α-decay

Whenever an α- particle is emitted by a radioactive nucleus the following conservation law must be obeyed.

(I) Conservation of charge and the number of nucleons:-

In α-decay, as in all nuclear reactions, the total charge and the total number of nucleons must be conserved. If A is a mass number and the Z the atomic number of the parent then $_ZP^A = {}_{Z-2}D^{A-4} + {}_2He^4$ where P and D refer to the parent and daughter nuclei. As a ~~example~~ particular example we have the decay of Bismuth 212 into Thallium 208 according to the reaction.

$$_{83}Bi^{212} = {}_{81}Tl^{208} + {}_2He^4.$$

It will be seen that the sum of the nucleon numbers on the right (208+4) is equal to the nucleons number on the left (212) and the sum of the units of charge on the right (81+2) is equal to the total charge (83) on the left.

(II) Conservation of linear momentum:-

The linear momentum must also be conserved in the

emission of α- particle. If the parent nucleus of mass M_p is at rest, then initial momentum $= 0$
If the daughter nucleus of mass M_d has a velocity V_d and the α-particle of mass m a velocity u, then
Final momentum $= M_d V_d + mu$.

$$\text{Hence } M_d V_d + mu = 0$$

$$\text{or } mu = -M_d V_d \quad \text{———— (ii)}$$

In other words, the daughter nucleus must have a velocity in a direction opposite to that ~~of~~ in which the α-particle is ejected.

(iii) Conservation of mass- energy:—
If E is the energy with which the α-particle is ejected and E_d is the K.E of the daughter, then according to the principle of Conservation of mass energy

$$M_p c^2 = M_d c^2 + mc^2 + E_d + E \quad \text{———— (iii)}$$

we have the K.E or disintigration energy of α-particle is $Q = (M_p - M_d - m)c^2$ ———— (iii)a
This can be put in the form

$$Q = E_d + E = \frac{1}{2} M_d V_d^2 + \frac{1}{2} mu^2 \quad \text{———— (iv)}$$

From equn (ii) $V_d = \dfrac{-mu}{M_d}$

$$\text{or } (V_d)^2 = \left(\frac{mu}{M_d}\right)^2$$

substituting in (iv) we have

$$Q = \frac{1}{2} mu^2 + \frac{1}{2} mu^2 \left(\frac{m}{M_d}\right)$$

$$= \frac{1}{2} mu^2 \left(1 + \frac{m}{M_d}\right) = E\left(1 + \frac{m}{M_d}\right)$$

As $Q = E\left(1 + \frac{m}{M_d}\right)$, the α-particle energy E is less than the disintegration energy Q.
For example, decay of Bi^{212} in to Thallium 208 with the emission of an α-particle, the K.E of the α-particle $E = 10.54$ Mev, the mass of the daughter nucleus is $212 - 4 = 208$ and mass of α-particle $= 4$.

$$\therefore Q = E\left(1 + \frac{m}{M_d}\right) = 10.54\left(1 + \frac{4}{208}\right) = 10.54 \times \frac{212}{208} = 10.74 \text{ Mev}$$

i.e. when Total disintegration energy available is 10.74 MeV, α-particle is emitted with an energy 10.54 MeV. The balance 0.2 MeV becomes the KE of daughter nucleus.

Energy of α-particle discrete in α-~~particle~~ decay :- The formation of an α-particle with in the nucleus makes available the kinetic energy the particle must have to escape from the nucleus. The K.E is known as the disintegration energy released in the process of emission of an α-particle from a heavy nucleus is given by ~~$Q = [M_p - (M_d + M_\alpha)]c^2$~~

$$Q = [M_p - (M_d + M_\alpha)]c^2$$ where M_p is the mass of the parent nucleus, M_d the mass of product or daughter nucleus and M_α the mass of α-particle emitted. Thus if the daughter nucleus does not carry any energy the α-particles has a discrete value of energy as all other factors constant. Even if the daughter nucleus carries some energy the α-particle energy will be less by the same amount but it will still have a discrete value.

Range of α-particle.

The α-particles have the property of ionising a gas. As the α-particles pass through gas, these lose energy by ionising the gas particles and slowed down. This process continues till the energy of the α-particles falls below the ionisation potential of the gas. After this, the α-particle captures two electrons and becomes a neutral helium atom.

The distance the α-particle travels in the gas before its energy falls below the ionisation potential of the gas is called its range in that gas.

The range is usually expressed in cm in air at 76 cm of mercury pressure and 15°C. The range depends upon

i) The initial energy of the α-particle

ii) The ionisation potential of the gas

iii) Nature and pressure of the gas.

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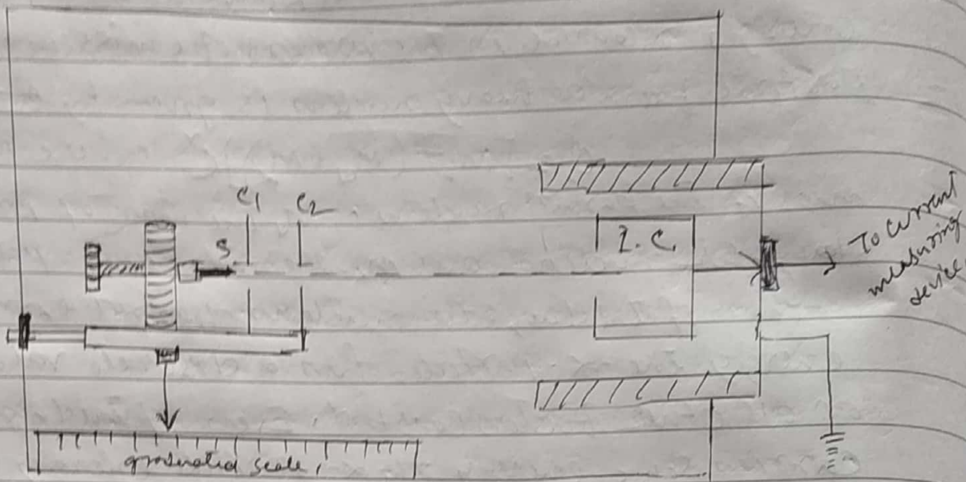
Determination of range of α - particle :-

The range of α - particle in air can be measured with the help of the apparatus shown in the fig below. The radioactive α emitting source S is placed on a movable block, the distance of which from an ionisation chamber I.C. can be adjusted and measured on a graduated scale.

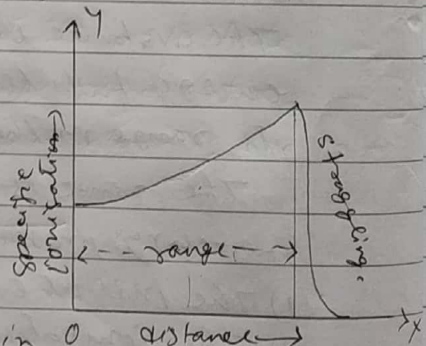


The narrow beam of α - particles coming out of collimating slits C_1 and C_2 after passing through a known thickness of air enters the ionisation chamber I.C, where ionisation take place and an ionisation current is setup. This current is measured by a sensitive current measuring device.

It is observed that as the distance between the source and the I.C. is increased, the ionisation current slowly rises to a maximum up to a certain distance and then drops suddenly to zero as shown in the fig. The distance corresponding to maximum ionisation current measures the range of the α-particle.

Straggling and its causes :-

A graph between sp. ionisation i.e the number of ions produced by α-particles per unit length of the path and distance in cm in air at 76 cm of mercury pressure and 15°C is shown in the fig. This curve known as Bragg's curve shows that specific ionisation during the path of the α - particles rises



slowly to a maximum value and then falls rapidly to zero making a slight ankle or tail in the curve before the zero line is reached. This tail represent the straggling effect.

The tail or ankle of the curve showing the straggling effect arises due to the following reasons.

(i) All the α-particles are not emitted from the source with the same initial energy (or velocity)

(ii) All the α-particles do not lose exactly the same amount of energy in their encounters with the molecules in their path.

Theory of α-decay of nuclei

According to the mass-energy condition of α-decay

$M_p c^2 = M_d c^2 + m_\alpha c^2 + E_d + E_\alpha$. where M_p is the mass of the parent nucleus, M_d that of the daughter nucleus, m_α of the α-particle, E_α the K.E with which the α-particle is ejected, E_d the kinetic energy imparted to the daughter nucleus.

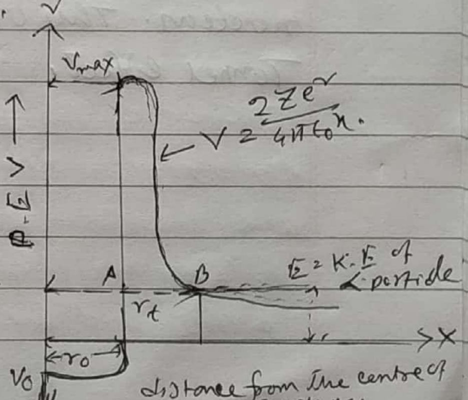
But even when the disintegration of a nucleus is energetically possible all the nuclei in a radioactive substance do not disintegrate immediately. This is because for a radioactive nucleus there exist a potential barrier which is a space in which the potential is so high that according to classical conceptions, an α-particle inside that barrier can not escape. The potential energy of the α-particle at a distance x from the centre of the nucleus is given by $V_x = \frac{2(Z_p - 2)e^2}{4\pi\epsilon_0 x} = \frac{2Z_d e^2}{4\pi\epsilon_0 x}$ where Z_p is the atomic nucleus of the parent nucleus and Z_d that of daughter nucleus. or $V_x = \frac{2Ze^2}{4\pi\epsilon_0 x}$ (Taking $Z_d = Z$)

This gives the hight of the potential barrier at a distance x from the centre of the nucleus.

The maximum hight of the potential barrier

$$V_{max} = \frac{2Ze^2}{4\pi\epsilon_0 r_0}$$

where r_0 is the sum of the radii of the nucleus and the α-particle.



The value of V_{max} for ${}_{92}U^{238}$ comes out to be 26 MeV. Hence according to classical theory, the energy required by the α-particle to escape from the nucleus must be more than 26 MeV. But it has been observed that α-particle ~~emitted~~ emitted by ${}_{92}U^{238}$ have an energy only 4.18 MeV. So how is it possible for the α-particle of energy 4.18 MeV to cross the barrier of 26 MeV which should required an energy 7 times as much.

The escape of an α-particle from a radio active nucleus can be explained on the basis of the quantum theory by an application of wave mechanics. Wave mechanical analysis shows that there is often a small but finite probability for the occurrence of events, which are normally absolutely forbidden by classical mechanics. In quantum mechanics, the probability of locating the α-particle is given by its wave function, The wave function for the potential is oscillatory within the potential well. i.e at distance less than r_0 and is highly attenuated through the potential barrier. i.e for distance greater than r_0 but less than r_1 where r_1 is the distance from the centre of the nucleus where the potential energy is equal to the kinetic energy actually possessed by the α-particle. The value of r_1 for ${}_{92}U^{238}$ is 5×10^{-14} m. whereas r_0 is nearly 1×10^{-14} m. The value of $(r_1 - r_0)$ gives the thickness of the potential barrier, which the α-particle has to cross. Outside the potential ~~the wave~~ barrier the wave function is again oscillatory and has a small but finite amplitude. In other words, it means that there is a small but finite probability that the α-particle originally within the nucleus may be found outside the nucleus. This unique quantum phenomenon is known as Tunnel effect.

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Application of Tunnel effect in α-decay

Tunnel effect :- The transmission probability that an α-particle may penetrate through the potential barrier is given by

$T = e^{-2k_2 a}$ ——— (1)

where $k_2^2 = \frac{2m}{\hbar^2}(V_0 - E)$; V_0 = constant height and a the width of the potential barrier, m the reduced mass of the α-particle and E its energy ($E < V_0$)

It is clear from the relation, $T = e^{-2k_2 a}$ that although the energy of the α-particle is less than the barrier height and classically it is not possible for the α-particle to cross the barrier height $V_0 > E$, quantum mechanically it is possible as the transmission probability is not zero.

According to quantum mechanics, α-particle exist as an entity within the heavy nucleus. The α-particle is in constant motion and is contained in the nucleus by the surrounding potential barrier. ~~It~~ It bounces back and forth the barrer walls. In each collision with the 'wall', there is a finite probability given by eqn (1) that the particle will leak through the barrier. In fact the α-particle within the nucleus must present itself again and again at the barrier surface until conditions are ripe for penetration or leakage. In $_{92}U^{238}$ the α-particle must make 10^{38} tries, ie 10^{38} tries per second for 10^{16} seconds or 10^9 years before it escapes.

As there is a finite probability for the α-particle to escape through the potential barrier of height V_0 greater than its ~~energy~~ energy E, the phenomenon is known as barrier penetration or tunnel effect.

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