MPM: 203 NUCLEAR AND PARTICLE PHYSICS

UNIT –I: Nuclear Stability

Lecture-12

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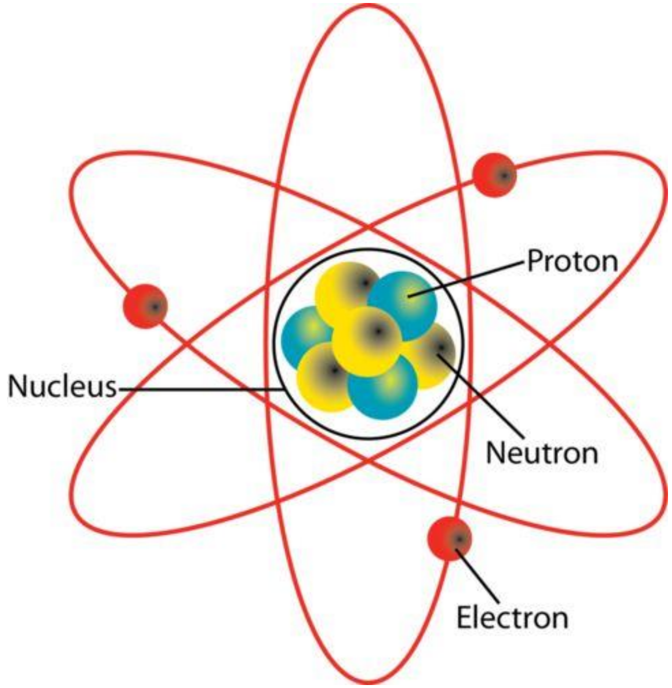
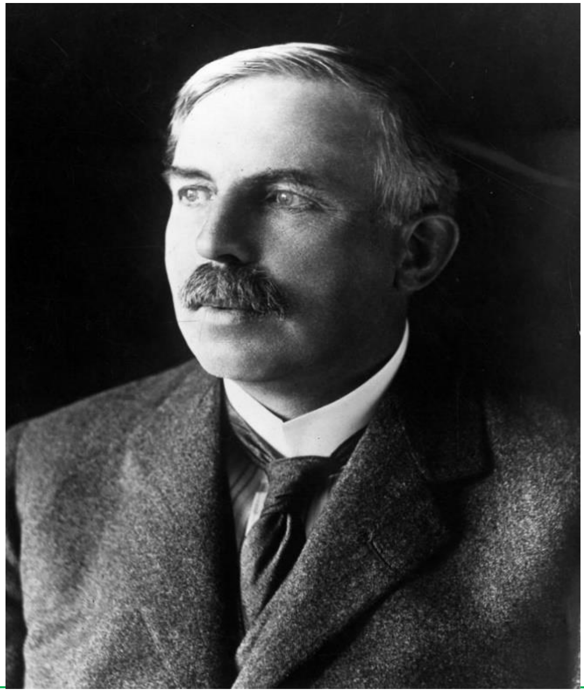




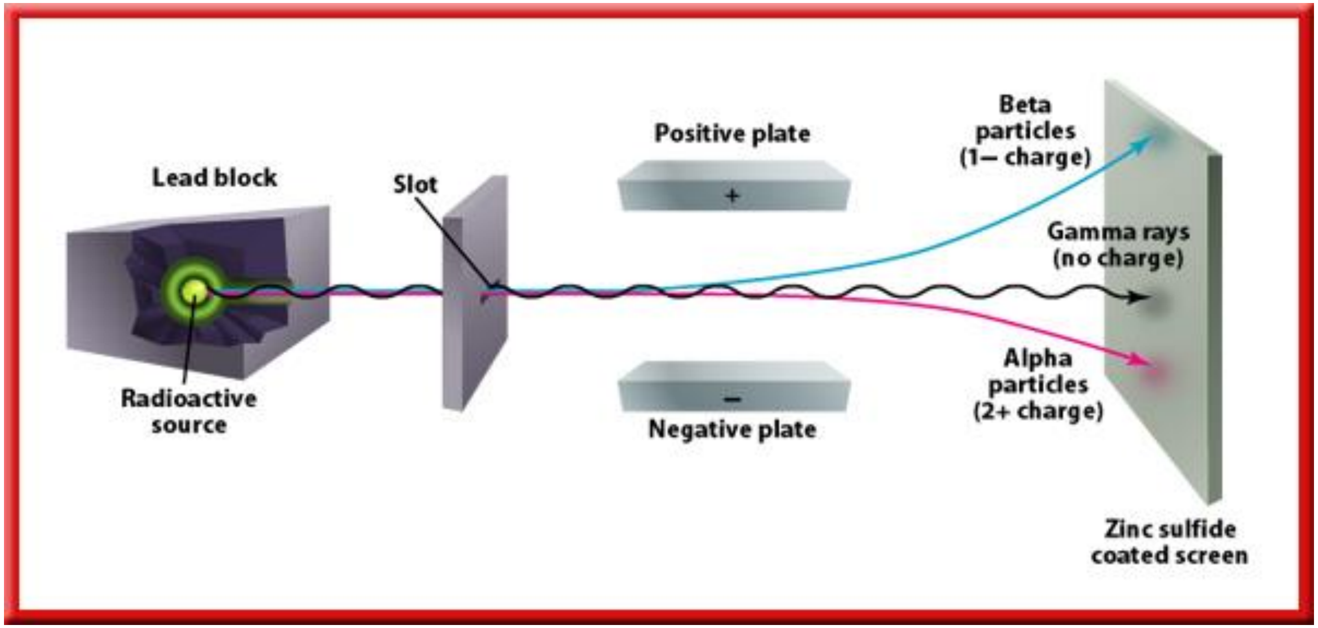
Alpha, Beta, and Gamma Decay

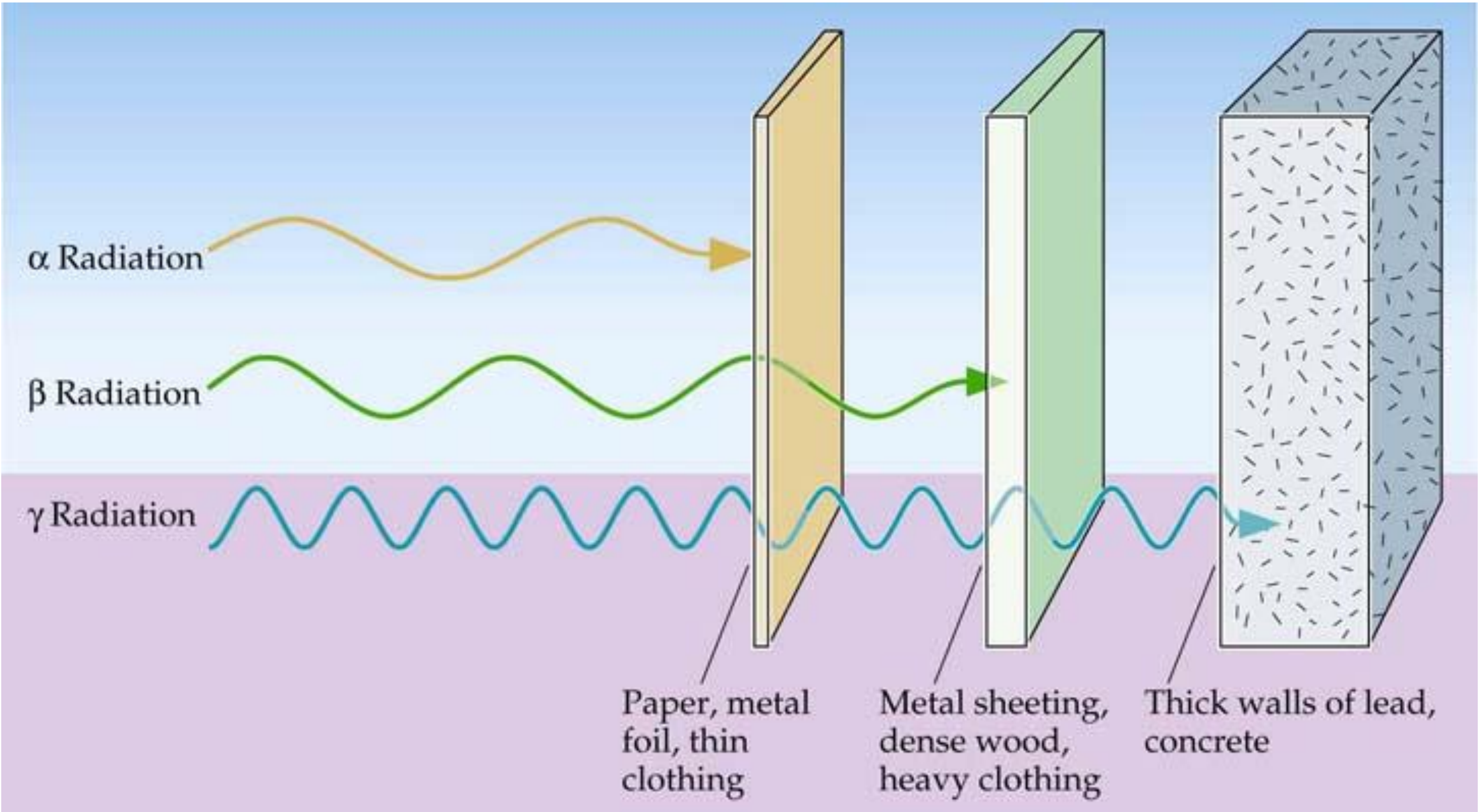
When a nucleus decays, all the conservation laws must be observed:

- Mass-energy
- Linear momentum
- Angular momentum
- Electric charge
- **Conservation of nucleons**
    - The total number of nucleons (*A*, the mass number) must be conserved in a typical (relatively low energy) nuclear reaction or decay.

Types of Radiation

- The effect of an electric field on three types of radiation is shown.
- Positively charged alpha particles are deflected toward the negatively charged plate.

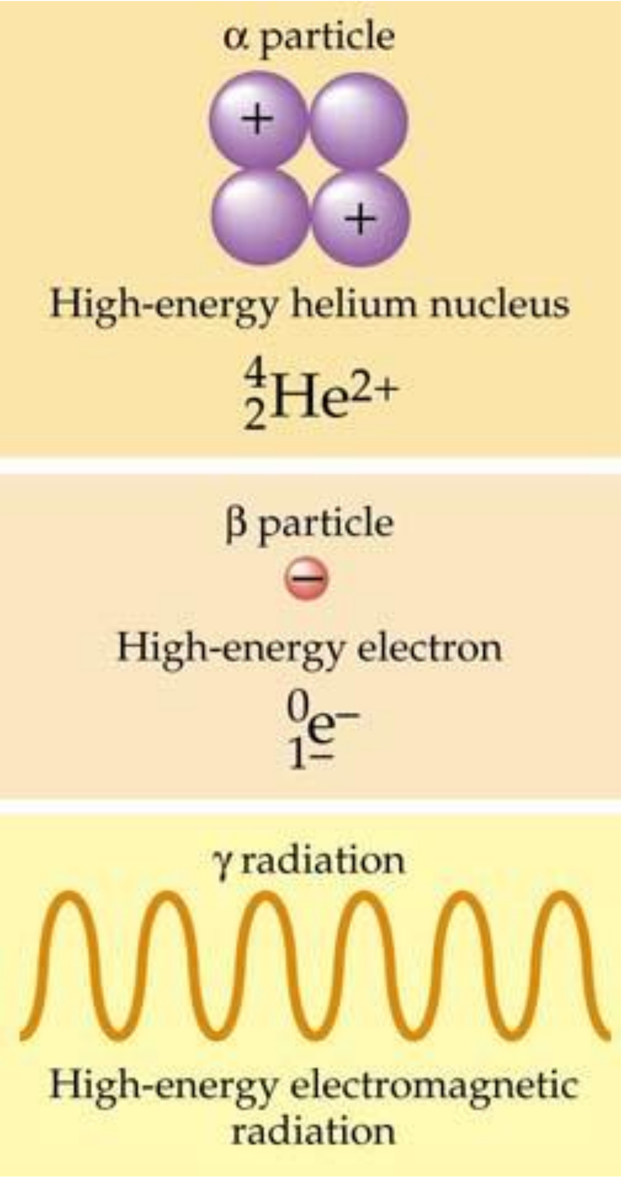



α Radiation
β Radiation
γ Radiation
Paper, metal foil, thin clothing
Metal sheeting, dense wood, heavy clothing
Thick walls of lead, concrete

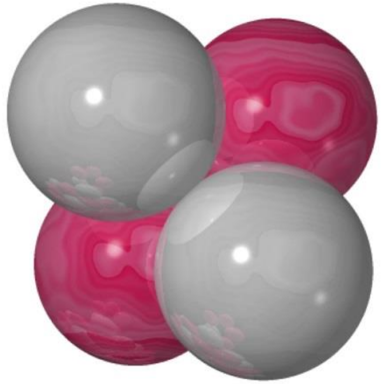
Products of Natural Radioactivity

Particle*	Symbol	Charge	Mass Number	Identity
Alpha	$^{4}_{2}\alpha$	2+	4	Helium nucleus
Beta	$^{0}_{-1}\beta$	1-	0	Electron
Gamma	$^{0}_{0}\gamma$	0	0	Proton of light

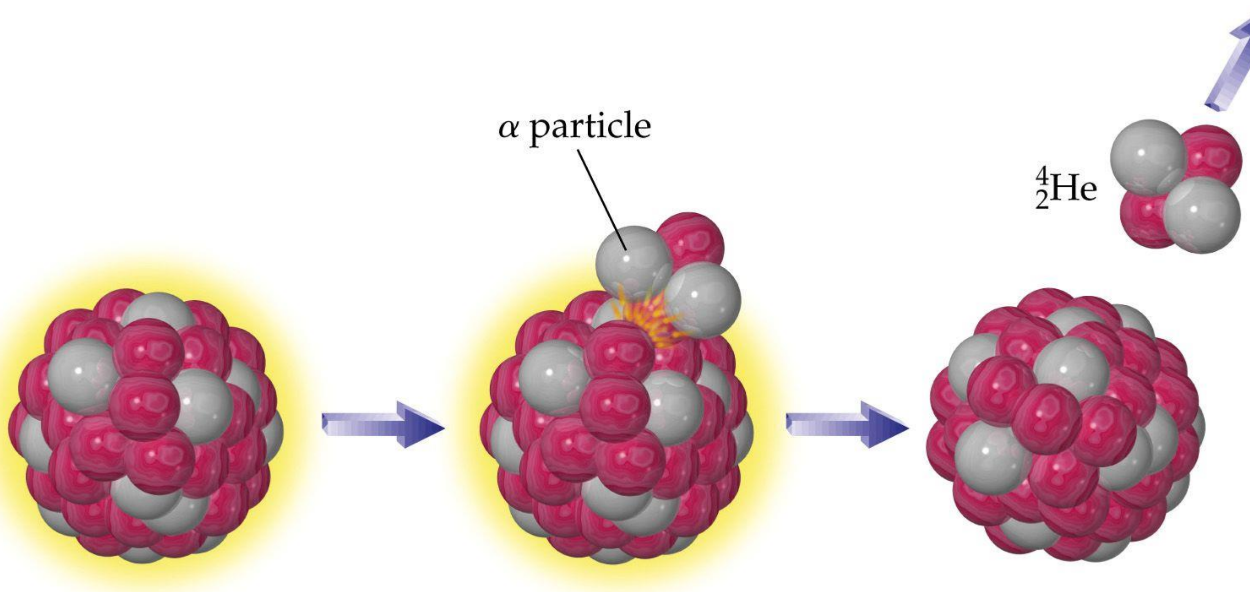
***Sometimes a stream of any of these types of particles is called a ray, as in gamma ray,**


α particle
+
+
High-energy helium nucleus
$^{4}_{2}He^{2+}$
β particle
High-energy electron
$^{0}_{-1}e^{-}$
γ radiation
High-energy electromagnetic radiation

- alpha particle emission
  - loss of a helium nucleus.



An α particle

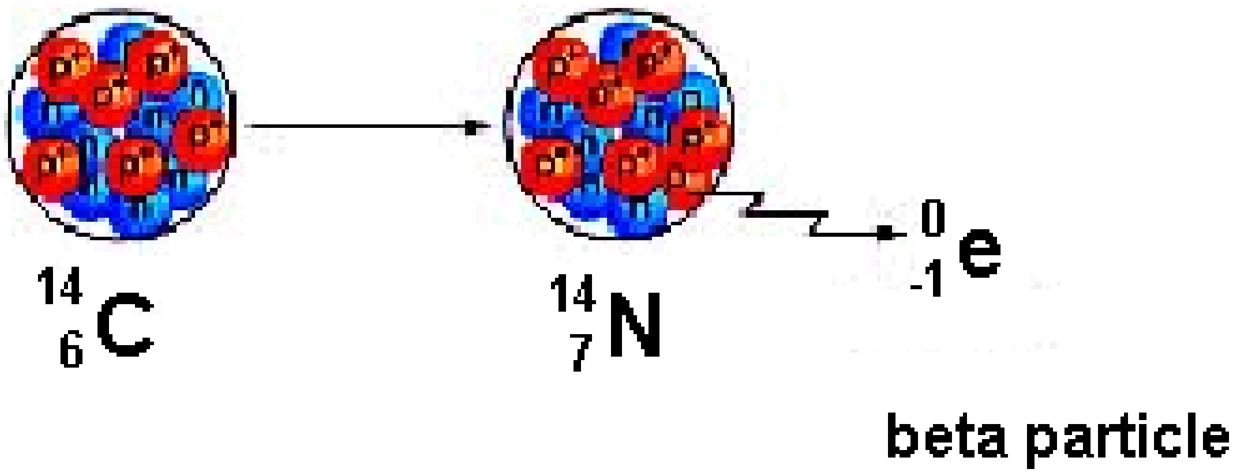


Parent nuclide | Daughter nuclides

$$^{238}_{92}\mathrm{U} \longrightarrow \ ^{234}_{90}\mathrm{Th} + \ ^{4}_{2}\mathrm{He}$$

Types of radioactive decay

Beta decay, Nuclear changes that accompany the emission of a beta particle.



β- Particle Emission

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

γ-Particle Emission

- **Gamma rays are high-energy (short wavelength) electromagnetic radiation. They are denoted by the symbol.** $^{0}_{0}\gamma$

- **As you can see from the symbol, both the subscript and superscript are zero.**

- **Thus, the emission of gamma rays does not change the atomic number or mass number of a nucleus.**

- **Gamma rays almost always accompany alpha and beta radiation, as they account for most of the energy loss that occurs as a nucleus decays.**

Alpha, Beta, and Gamma Decay

- Let the radioactive nucleus ${}^{A}_{Z}X$ be called the parent and have the mass $M\left({}^{A}_{Z}X\right)$

- Two or more products can be produced in the decay.
- Let the original one be M_y (mother) and the mass of the subsequent one (*daughter*) be M_D.
- The conservation of energy is $M\left({}^{A}_{Z}X\right) = M_D + M_y + Q/c^2$

- where Q is the energy released (**disintegration energy**) and equal to the total kinetic energy of the reaction products.

$$Q = \left[M\left({}^{A}_{Z}X\right) - M_D - M_y\right]c^2$$

- If $Q > 0$, a nuclide is unstable and may decay.
- If $Q < 0$, decays emitting nucleons do not occur.

Alpha Decay

- The nucleus ^{4}He has a binding energy of 28.3 MeV.
- If two protons and two neutrons in a nucleus are bound by less than 28.3 MeV, then the emission of an alpha particle (alpha decay) is possible.

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}D + \alpha$$

$$Q = \left[M\left({}^{A}_{Z}X \right) - M\left({}^{A-4}_{Z-2}D \right) - M\left({}^{4}\text{He} \right) \right] c^2$$

Is also a nucleus

- If $Q > 0$, alpha decay is possible.

$$^{230}_{92}\text{U} \rightarrow \alpha + {}^{226}_{90}\text{Th}$$

The appropriate masses are

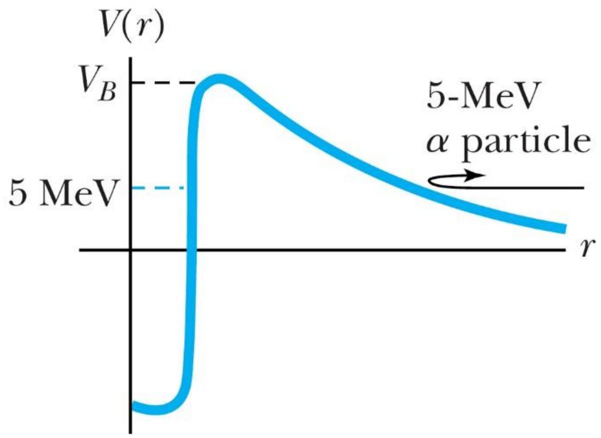
$$M\left({}^{230}_{92}\text{U} \right) = 230.033927 \text{ u}; \; M\left({}^{4}\text{He} \right) = 4.002603 \text{ u}; \; M\left({}^{226}_{90}\text{Th} \right) = 226.024891 \text{ u}$$

Alpha Decay

$$Q = \left[M(^{230}\mathrm{U}) - M(^{226}\mathrm{Th}) - M(^{4}\mathrm{He})\right]c^2$$

$$= [230.033927\ \mathrm{u} - 226.024891\ \mathrm{u} - 4.002603\ \mathrm{u}]c^2\left(\frac{931.5\ \mathrm{MeV}}{c^2 \cdot \mathrm{u}}\right) = 6.0\ \mathrm{MeV}$$

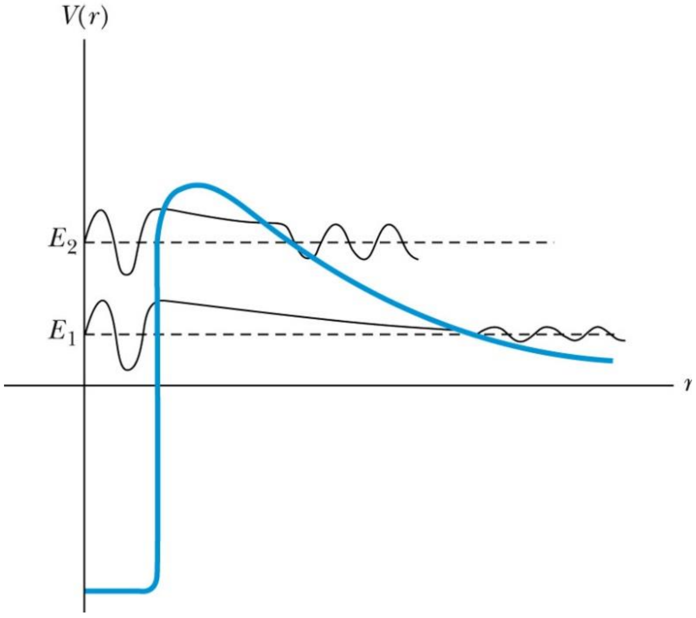
In order for alpha decay to occur, two neutrons and two protons group together within the nucleus prior to decay and the alpha particle overcomes the nuclear attraction from the remaining nucleons and escapes through the potential energy barrier by tunneling.



The potential energy diagram of alpha particle

Alpha Decay

- The barrier height V_B is greater than 20 MeV.
- The kinetic energies of alpha particles emitted from nuclei range from 4-8 MeV.
- It is impossible classically for the alpha particle to escape the nucleus, but the alpha particles are able to tunnel through the barrier.



At higher energy, E_2, α-particle has much higher tunneling probability than at lower energy, E_1, corresponding to shorter lifetimes.

Alpha Decay

- **Assume the parent nucleus is initially at rest so that the total momentum is zero.**
- **The final momenta of the daughter p_D and alpha particle p_α have the same magnitude and opposite directions.**

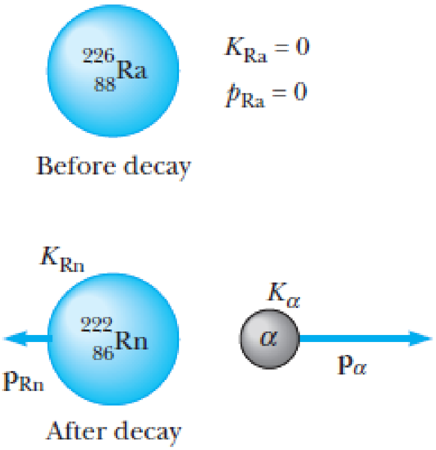


Figure 13.16 Alpha decay of radium. The radium nucleus is initially at rest. After the decay, the radon nucleus has kinetic energy K_{Rn} and momentum $\mathbf{p}_{Rn}$, and the alpha particle has kinetic energy K_α and momentum $\mathbf{p}_\alpha$.

So all alpha particles have the about the same momentum and kinetic energy

EXAMPLE 13.8 The Energy Liberated When Radium Decays

The ^{226}Ra nucleus undergoes alpha decay according to Equation 13.12. Calculate the Q value for this process. Take the atomic masses to be 226.025 406 u for ^{226}Ra, 222.017 574 u for ^{222}Rn, and 4.002 603 u for $^{4}_{2}$He, as found in Appendix B.

Solution Using Equation 13.16, we see that

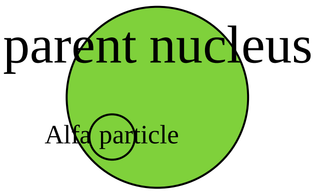
$$Q = (M_X - M_Y - M_\alpha) \times 931.494 \frac{\text{MeV}}{\text{u}}$$

$$= (226.025\,406\text{ u} - 222.017\,574\text{ u} - 4.002\,603\text{ u}) \times 931.494 \frac{\text{MeV}}{\text{u}}$$

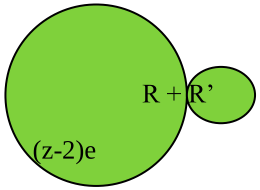
$$= (0.005\,229\text{ u}) \times \left(931.494 \frac{\text{MeV}}{\text{u}}\right) = 4.87\text{ MeV}$$

Gamow's Theory of Alfa Decay

- Let us consider a big nucleus within which alfa particle is formed.



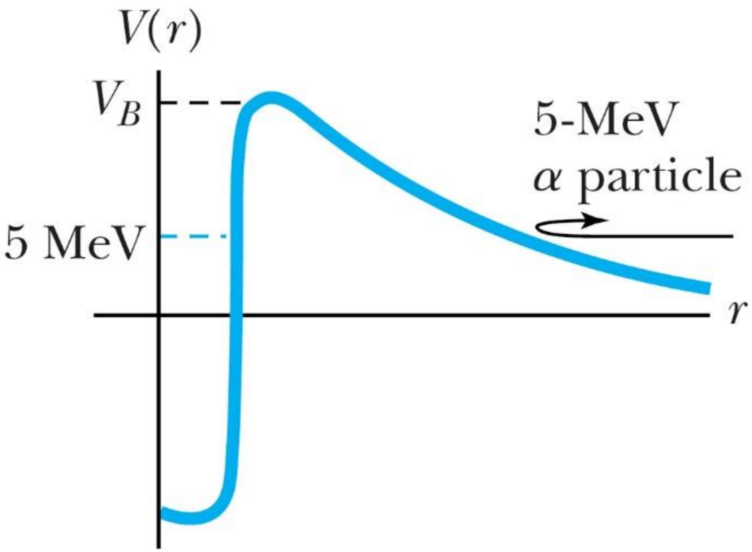
- Let r is the separation between the center of alfa particle and the nucleus.



- V(r) = Nuclear attraction potential for r<R
- Coulomb repulsive potential for r> (R+R')
- If alfa particle will be inside the nucleus Coulomb potential will be very small.

Gamow's Theory of Alfa Decay

- Coulomb potential can be given as
- $V_c = \frac{(Z-2)e.2e}{4\pi\epsilon_0 r}$
- Maximum Barrier height for Z=72 and A= 200
- r = 1.25 Fm $A^{1/3}$
- = 1.25 Fmx6 = 7.5 Fm



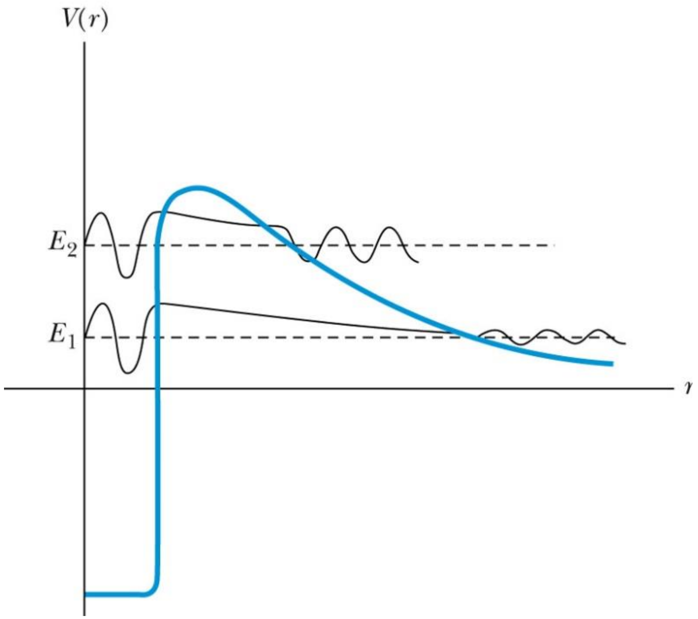
- Putting these values in above equation we get
- V_c = 25 MeV (Approx.)
- But the energy of the alfa particle is 4-5 MeV.

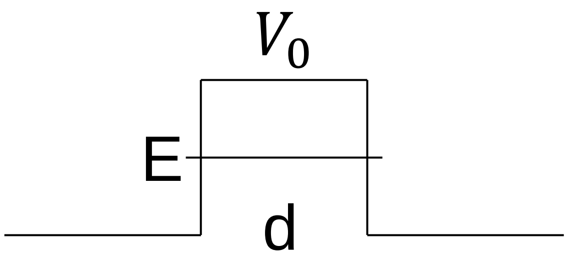
Gamow's Theory of Alfa Decay

- From R to the point of Penetration is known as forbidden energy.

- Since the Alfa particle has its energy less that the barrier height so classically it can not cross this barrier.

- But with quantum mechanically it is possible
- The probability of barrier penetration is given as
- $e^{-2\gamma d}$
- Where $\gamma = \sqrt{\frac{2m}{\hbar^2}}\,(V_0\text{-E})$





Gamow's Theory of Alfa Decay

- Above equation is valid for rectangular well potential but in the present case there is exponential decay in the potential.

- We approximate it for our present case and we take the small strip and instead of γd we will use
- $\gamma d = \int \gamma(r)dr$

- Where $\gamma(r) = \sqrt{\frac{2m}{\hbar^2}}$ (V-E)

- And V(r) = $\frac{2(Z-2)e^2}{4\pi\epsilon_0 r}$