Course: (CBCS) B.Sc. (H)-Physics [Section-A]

(32221402) Elements of Modern Physics

Part & Semester – II & IV

Lecture-5

Dear Students

Hope all of you are well and taking all the necessary precautions in this difficult time.

In our last class, we have discussed α, β, γ decay in detail, electron-positron pair creation by gamma photon in the vicinity of the nucleus and Fission, Fusion. Now, I am going to discuss about the thermonuclear reactions.

In our next lecture, we will discuss about the last unit of this course (LASER). Apart from this, all of you can contact me through Email, Whatsapp or Mobile for any quarry related to our course of Elements of Modern Physics.

Thanking you.

With Best Wishes

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Nuclear Reactions

- **Compound Nucleus:**

  The compound nucleus theory states that there are two steps involved in a nuclear disintegration and they are (i) the capture of the incident particle A by the target nucleus B forming a compound nucleus C^* in an excited state

(ii) the de-excitation of the compound nucleus C^* into a product nucleus D and the emission of a particle E or a $\gamma-$photon .

So, the nuclear reaction may be represented as $A+B \rightarrow C^* \rightarrow D+E$.

- Rutherford's first artificial nuclear transmutation may therefore be represented as

  $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{18}_{9}F^* \rightarrow ^{17}_{8}O + ^{1}_{1}H$

- **Classification of nuclear reactions:**

(i) **Elastic scattering:** In elastic scattering, the same particles are scattered in different directions and there is no loss of energy. The residual nucleus is the same as the target nucleus and is left in the same state (ground state) as the latter so that it can be represented as X(x, y)X. An example is the scattering of neutrons by graphite: $^{12}C(n,n)\,^{12}C$. **Example:** $_2He^4 + _{79}Au^{197} \rightarrow _{79}Au^{197} + _2He^4$

(ii) **Inelastic scattering:** In inelastic scattering, the same particles are scattered in different directions with different energy, as there is loss of energy due to collision. The residual nucleus which is the same as target nucleus is left in an excited state so that the process can be represented as $X(x,y)X^*$. An example is the collision of fast neutrons with U-238.

(iii) **Radiative capture:** In radiative capture, the incident particle is absorbed or captured by the target nucleus to form the excited compound nucleus which disintegrates to produce one or more $\gamma-$photons and goes down to the ground state. The process may be represented as $X(x,\gamma)Y^*$.

Example: $_{92}U^{235} + _0n^1 \longrightarrow _{92}U^{236}$.

(iv) **Reaction of transformation:** Here the oncoming particle is retained in the nucleus and the compound nucleus emits a different particle so that the product nucleus is different from target nucleus, e.g. $^9Be(\alpha,n)^{12}C$

(v) **Photo-disintegration:** In photo-disintegration, a very energetic photon is absorbed by the target nucleus so that it is raised to an excited state and subsequently disintegrates. It can be represented as $X(\gamma,y)Y$. **Example:** $_1H^2 + \gamma \longrightarrow _1H^1 + _0n^1$.

(vi) **Stripping reactions:** In stripping reactions, one or more nucleons from the projectile are captured by the target nucleus, the remaining stripped nucleus is emitted in a different direction.

Example: $_{29}Cu^{63} + _1d^2 \longrightarrow _{29}Cu^{64} + _1H^1$

(vii) **Direct reactions:** A collision of an incident particle with the nucleus may immediately pull one of the nucleons out of the target nucleus and is called 'pick up reaction'.

Example: $_1H^1 + _6C^{13} \longrightarrow _1d^2 + _6C^{12}$

- **Conservation in Nuclear reactions:**

  (i) Conservation of mass number
  (ii) Conservation of atomic number
  (iii) Conservation of energy (including mass-energy)
  (iv) Conservation of linear momentum

(v) Conservation of angular momentum. (vi) Conservation of parity
(vii) Conservation of isotopic spin

- **Q-value and threshold energy of nuclear reaction:**

The law of conservation of energy and momentum imposes certain restrictions on the reactions. These restrictions are called the kinematic restrictions and this mathematical methods is known as kinematics.

Consider the nuclear reaction

$$x + X \longrightarrow y + Y$$

Where x, X, y and Y are the bombarding particle, target nucleus, outgoing particle and product nucleus respectively. It is assumed that the target nucleus is in rest. Since total energy is conserved in the nuclear reaction, therefore we get,

$$\left(m_x c^2 + E_x\right) + M_X c^2 = \left(E_y + m_y c^2\right) + \left(E_Y + M_Y c^2\right)$$

E_x, E_y and E_Y are the kinetic energies of respective particles.

Now the quantity $Q = E_y + E_Y - E_x \Rightarrow Q = \left(m_x + M_X - m_y - M_Y\right)c^2$

Where Q is called the Q-value of nuclear reaction.

(i) If Q is positive, the reaction is said to be exoergic (exothermic) and
(ii) If Q is negative, the reaction is called endoergic (endothermic).

The minimum K.E. required for incident particle (x) to start the nuclear reaction is called the threshold energy $(E_x)^{th}$. The relation between Q-values and threshold energy is:

$$\boxed{E_x^{th} = -Q\frac{\left(m_y + M_Y\right)}{\left(M_Y + m_y - m_x\right)}}$$

If $E_x^{th} = 0$ for exoergic or exothermic reactions i.e. these reaction are spontaneous process.

- **Mechanism of nuclear reactions:**
- **Transmutation by protons:**

(a) (p, α) reactions:

(i) ${}_3Li^7 + {}_1H^1 \rightarrow \left({}_4Be^8\right)^* \rightarrow {}_2He^4 + {}_2He^4$

(ii) ${}_3Li^6 + {}_1H^1 \rightarrow \left({}_4Be^7\right)^* \rightarrow {}_2He^3 + {}_2He^4$

(iii) ${}_4Be^9 + {}_1H^1 \rightarrow \left({}_5B^{10}\right)^* \rightarrow {}_3Li^6 + {}_2He^4$

(iv) ${}_5B^{11} + {}_1H^1 \rightarrow \left({}_6C^{12}\right)^* \rightarrow {}_4Be^8 + {}_2He^4$

(v) ${}_9F^{19} + {}_1H^1 \rightarrow \left({}_{10}Ne^{20}\right)^* \rightarrow {}_8O^{16} + {}_2He^4$

(b) (p–n) Reaction:

(i) ${}_5B^{11} + {}_1H^1 \rightarrow \left({}_6C^{12}\right)^* \rightarrow {}_6C^{11} + {}_0n^1$

(ii) ${}_8O^{18} + {}_1H^1 \rightarrow \left({}_9F^{19}\right)^* \rightarrow {}_9F^{18} + {}_0n^1$

(iii) ${}_{11}Na^{23} + {}_1H^1 \rightarrow \left({}_{12}Mg^{24}\right)^* \rightarrow {}_{12}Mg^{23} + {}_0n^1$

(iv) ${}_{28}Ni^{58} + {}_1H^1 \rightarrow \left({}_{29}Cu^{59}\right)^* \rightarrow {}_{29}Cu^{58} + {}_0n^1$

(v) ${}_{29}Cu^{65} + {}_1H^1 \rightarrow \left({}_{30}Zn^{66}\right)^* \rightarrow {}_{30}Zn^{65} + {}_0n^1$ (usually endoergic)

(c) (p, d) reaction:

(i) $_3Li^7 +_1 H^1 \rightarrow_3 Li^6 + {}_1H^2$

(ii) $_4Be^9 +_1 H^1 \rightarrow_4 Be^8 + {}_1H^2$

(d) Proton capture:

Compound nucleus in excited states come to ground state with $\gamma -$ ray photon.

(i) $_3Li^7 +_1 H^1 \rightarrow \left({}_4Be^8\right)^* \rightarrow {}_4Be^8 + \gamma$

(ii) $_6C^{12} +_1 H^1 \rightarrow \left({}_7N^{13}\right)^* \rightarrow {}_7N^{13} + \gamma$

(iii) $_7N^{14} +_1 H^1 \rightarrow \left({}_8O^{15}\right)^* \rightarrow {}_8O^{15} + \gamma$

(iv) $_9F^{19} +_1 H^1 \rightarrow \left({}_{10}Ne^{20}\right)^* \rightarrow {}_{10}Ne^{20} + \gamma$

(v) $_{13}Al^{27} +_1 H^1 \rightarrow \left({}_{14}Si^{28}\right)^* \rightarrow {}_{14}Si^{28} + \gamma$

(vi) $_{24}Cr^{50} +_1 H^1 \rightarrow \left({}_{25}Mn^{51}\right)^* \rightarrow {}_{25}Mn^{51} + \gamma$

If incident proton has an energy (> 20 MeV) the compound nucleus has sufficient excitation energy to permit the expulsion of two or more nucleons.

(2) Transmutation by Neutrons:-

Neutrons have no electric charge and can penetrate +vely charged nuclei without any experience of repulsive electrostatic force.

(a) (n–α) reaction:

With slow Neutrons

(i) $_3Li^6 + {}_0n^1 \rightarrow \left({}_3Li^7\right)^* \rightarrow_1 H^3 +_2 He^4$

(ii) $_5B^{10} + {}_0n^1 \rightarrow \left({}_5B^{11}\right)^* \rightarrow_3 Li^7 +_2 He^4$

(iii) $_{13}Al^{27} + {}_0n^1 \rightarrow \left({}_{13}Al^{28}\right)^* \rightarrow_{11} Na^{24} +_2 He^4$

(iv) $_7N^{14} + {}_0n^1 \rightarrow \left({}_7N^{15}\right)$

(v) $_5B^{11} +_2 He^4$

(vi) $_3Li^7 +_2 He^4 + {}_2He^4$

Capture of fast Neutrons - emission of α - particle are usually radioactive

(i) $_{11}Na^{23} +_0 n^1 \rightarrow \left({}_{11}Na^{24}\right)^* \rightarrow_9 F^{20} + {}_2He^4$ followed by $_9F^{20} \rightarrow_{10} Ne^{20} + \beta^-$

(ii) $_{13}Al^{27} +_0 n^1 \rightarrow \left({}_{13}Al^{28}\right)^* \rightarrow_{11} Na^{24} + {}_2He^4$ followed by $_{11}Na^{24} \rightarrow_{12} Mg^{24} + \beta^-$

(b) (n, p) reaction: Proton in the nucleus is replaced by neutron mass no, does not change but change decreases by one unit.

(i) $_7N^{14} + {}_0n^1 \rightarrow \left({}_7N^{15}\right)^* \rightarrow_6 C^{14} +_1 H^1 + Q$ followed by $_6C^{14} \rightarrow_7 N^{14} + \beta^- + E_{max}$

(ii) $_2He^3 + {}_0n^1 \rightarrow \left({}_2He^4\right)^* \rightarrow_1 H^3 +_1 H^1 + Q$ followed by $_1H^3 \rightarrow_2 He^3 + \beta^- + E_{max}$

(iii) $_{17}Cl^{35} + {}_0n^1 \rightarrow \left({}_{17}Cl^{36}\right)^* \rightarrow_{16} S^{35} +_1 H^1 + Q$ followed by $_{16}S^{35} \rightarrow {}_{17}Cl^{35} + \beta^- + E_{max}$

With fast neutrons:

(i) $_{13}Al^{27} +_0 n^1 \rightarrow \left({}_{13}Al^{28}\right)^* \rightarrow_{12}Mg^{27} + {}_1H^1$

(ii) $_{16}S^{32} +_0 n^1 \rightarrow \left({}_{16}S^{33}\right)^* \rightarrow_{15}P^{32} + {}_1H^1$

(iii) $_{29}Cu^{65} +_0 n^1 \rightarrow \left({}_{29}Cu^{66}\right)^* \rightarrow_{28}Ni^{65} + {}_1H^1$

(iv) $_{30}Zn^{64} +_0 n^1 \rightarrow \left({}_{30}Zn^{65}\right)^* \rightarrow_{29}Cu^{64} + {}_1H^1$

(c) $(n-\gamma)$ **Reaction:**

(i) $_1H^1 + {}_0n^1 \rightarrow \left({}_1H^2\right)^* \rightarrow {}_1H^2 + \gamma$

(ii) $_1H^2 + {}_0n^1 \rightarrow \left({}_1H^3\right)^* \rightarrow {}_1H^3 + \gamma$

Product Nucleus is Radioactive:

(i) $_{45}Rh^{103} + {_0n^1} \rightarrow \left({_{45}Rh^{104}}\right)^* \rightarrow {_{45}Rh^{104}} + \gamma$ (ii) $_{49}In^{115} + {_0n^1} \rightarrow \left({_{49}In^{116}}\right)^* \rightarrow {_{49}In^{116}} + \gamma$

(iii) $_{92}U^{238} + {_0n^1} \rightarrow \left({_{92}U^{239}}\right)^* \rightarrow {_{92}U^{239}} + \gamma$ (iv) $_{29}Cu^{65} + {_0n^1} \rightarrow \left({_{29}Cu^{66}}\right)^* \rightarrow {_{29}Cu^{66}} + \gamma$

(v) $_{79}Au^{65} + {_0n^1} \rightarrow \left({_{79}Au^{198}}\right)^* \rightarrow {_{79}Au^{198}} + \gamma$

(d) (n – d) and (n – t) reaction: Bombardment of 90 MeV neutrons: $_7N^{14} + {_0n^1} \rightarrow {_6C^{12}} + {_1H^3}$

(e) (n – 2n) reaction: one neutron captured by nucleus and 2 neutrons are emitted. $Q < 0$ fast neutron are needed . Most cases residue nucleus unstable -followed by positron emission.

(i) $_6C^{11} + {_0n^1} \rightarrow \left({_6C^{13}}\right)^* \rightarrow {_6C^{11}} + 2\,{_0n^1}$ (ii) $_{19}K^{39} + {_0n^1} \rightarrow \left({_{19}K^{40}}\right)^* \rightarrow {_{19}K^{38}} + 2\,{_0n^1}$

(iii) $_{51}Sb^{121} + {_0n^1} \rightarrow \left({_{51}Sb^{122}}\right)^* \rightarrow {_{51}Sb^{120}} + 2\,{_0n^1}$

(f) Neutron - Three or more particles: Incident Neutron ~ 30 MeV sufficient energy to overcome coulomb Barrier, 3 neutrons or even 2 neutron and a proton are ejected from compound nucleus Neutron (~ 100 MeV) Nuclei with moderate mass no. undergo spallation and those of high mass no. eg. Bi and Pb suffer fission probably accompanied by spallative.

- **(3) Transmutation by Deuteron:** High energy Deuteron.

(a) $(d-\alpha)$ reaction

(i) $_3Li^6 + {_1H^2} \rightarrow \left({_4Be^8}\right)^* \rightarrow {_2He^4} + {_2He^4}$ (ii) $_8O^{16} + {_1H^2} \rightarrow \left({_9F^{18}}\right)^* \rightarrow {_7N^{14}} + {_2He^4}$,

(iii) $_{10}Ne^{20} + {_1H^2} \rightarrow \left({_{11}Na^{22}}\right)^* \rightarrow {_9F^{18}} + {_2He^4}$

(iv) $_{12}Mg^{26} + {_1H^2} \rightarrow \left({_{13}Al^{28}}\right)^* \rightarrow {_{11}Na^{24}} + {_2He^4}$,

(v) $_{13}Al^{27} + {_1H^2} \rightarrow \left({_{14}Si^{29}}\right)^* \rightarrow {_{12}Mg^{25}} + {_2He^4}$

(b) (d – p) Reaction: Isotope creation

(i) $_6C^{12} + {_1H^2} \rightarrow \left({_7N^{14}}\right)^* \rightarrow {_6C^{13}} + {_1H^1}$ (ii) $_3Li^7 + {_1H^2} \rightarrow \left({_4Be^9}\right)^* \rightarrow {_3Li^8} + {_1H^1}$

(iii) $_{11}Na^{23} + {_1H^2} \rightarrow \left({_{12}Mg^{25}}\right)^* \rightarrow {_{11}Na^{24}} + {_1H^1}$ (iv) $_{15}P^{31} + {_1H^2} \rightarrow \left({_{16}S^{33}}\right)^* \rightarrow {_{15}P^{32}} + {_1H^1}$

(v) $_{48}Cd^{114} + {_1H^2} \rightarrow \left({_{49}In^{116}}\right)^* \rightarrow {_{48}Cd^{115}} + {_1H^1}$

(vi) $_{83}Bi^{209} + {_1H^2} \rightarrow \left({_{84}Po^{211}}\right)^* \rightarrow {_{83}Bi^{210}} + {_1H^1}$

(c) (d – n) Reaction:

(i) $_3Li^7 + {_1H^2} \rightarrow \left({_4Be^9}\right)^* \rightarrow {_4Be^8} + {_0n^1}$ (ii) $_4Be^9 + {_1H^2} \rightarrow \left({_5B^{11}}\right)^* \rightarrow {_5B^{10}} + {_0n^1}$

(iii) $_{6}C^{12} + _{1}H^{2} \rightarrow \left(_{7}N^{14}\right)^{*} \rightarrow _{7}N^{13} + _{0}n^{1}$

When two Deuterons Interact both the (d, n) and (d, p) reactions have been obtained.

$$_{1}H^{2} + _{1}H^{2} \rightarrow _{2}He^{4} \rightarrow _{1}H^{3} + _{1}H^{1} + 4.02\ \text{MeV}$$

$$\rightarrow _{2}He^{3} + _{0}n^{1} + 3.25\ \text{MeV}$$

References:

1- Concepts of Modern Physics (Sixth Edition, TMH Pvt. Ltd.) by Arthur Beiser et.al.
2- Nuclear Physics (S. Chand Limited, 2008) by S. N. Ghoshal.
3- Nuclear Physics (Himalaya Publishing House, Mumbai) by D. C. Tayal.
4- Last year examination papers.

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