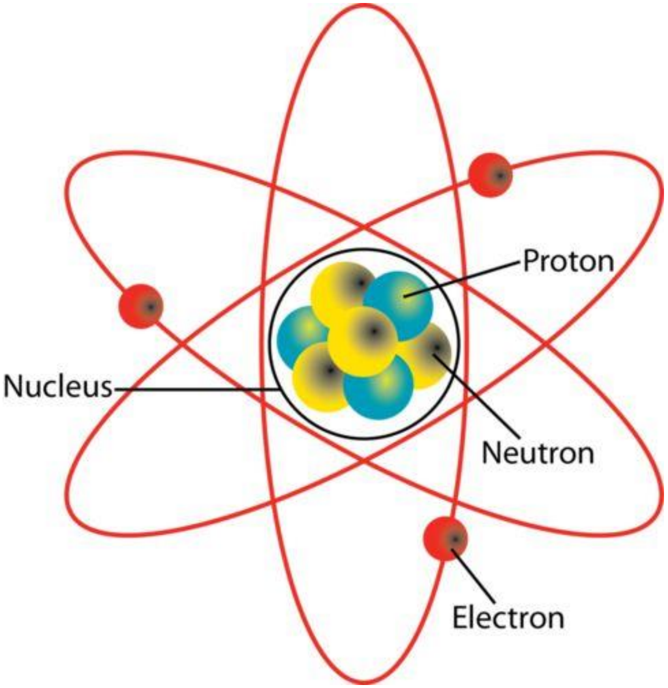
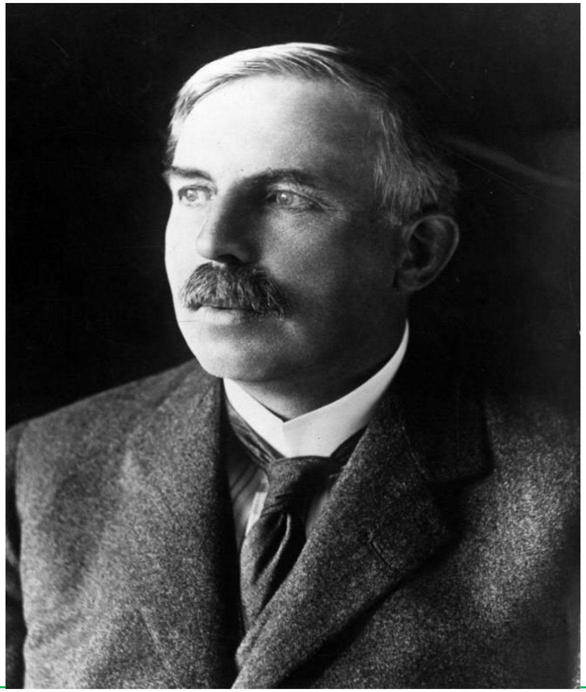
MPM: 203 NUCLEAR AND PARTICLE PHYSICS

UNIT –I: Nuclear Stability

Lecture-17

By Prof. B. K. Pandey, Dept. of Physics and Material Science





Nuclear Transmutation

The nuclear transmutation is a type of nuclear reaction in which the product nucleus Y differs from the target X. The product particle may be a charge …..

particle or neutron. The nuclear transmutation is represented by a type of nuclear reaction

$$a + X \rightarrow Y + b \quad i.e., \quad X\,(a, b)\,Y$$

where symbols have usual meanings. The first nuclear transmutation was done by Rutherford by bombarding α-particle on ${}_7N^{14}$,

i.e., $${}_2He^4 + {}_7N^{14} \rightarrow {}_8O^{17} + {}_1H^1.$$

The product nucleus is ${}_8O^{17}$ and product particle is proton.

With the discovery of high energy accelerators other particles such as protons, deuterons, neutrons were used as the bombarding particles. In this section we shall discuss the nuclear reactions where incident particles have energy less than 50 MeV.

Nuclear Transmutation

(a) Proton induced nuclear reactions : (*i.e.*, transmutation by protons) : The proton induced nuclear reactions are classified as (p, α), (p, n), (p, γ) and (p, d) reactions depending upon the formation of product particle.

(i) (p, α) reactions : A (p, α) reaction in general can be represented as

$$_{Z}X^{A} + {}_{1}H^{1} (\rightarrow {}_{Z+1}C^{A+1}) \rightarrow {}_{Z-1}Y^{A-3} + {}_{2}He^{4}$$

where C denotes the compound nucleus.

Such type of reactions were studied by Walton and Cockcroft in 1932. The bombarded $0 \cdot 7$ *MeV* protons on $_{3}Li^{7}$ nucleus

$$_{3}Li^{7} + {}_{1}H^{1} (\rightarrow {}_{4}Be^{8}) \rightarrow {}_{2}He^{4} + {}_{2}He^{4}$$

This reaction is historically important because it provided the earliest quantitative verification of Einstein's mass-energy equivalence relation $E = mc^2$, the other examples of (p, α) reactions are

$$_{3}Li^{6} + {}_{1}H^{1} [\rightarrow {}_{4}Be^{7}] \rightarrow {}_{2}He^{3} + {}_{2}He^{4}$$

$$_{4}Be^{9} + {}_{1}H^{1} [\rightarrow {}_{5}B^{10}] \rightarrow {}_{3}Li^{6} + {}_{2}He^{4}$$

$$_{13}Al^{27} + {}_{1}H^{1} [\rightarrow {}_{14}Si^{28}] \rightarrow {}_{12}Mg^{24} + {}_{2}He^{4}$$

$$_{5}B^{11} + {}_{1}H^{1} [\rightarrow {}_{6}C^{12}] \rightarrow {}_{4}Be^{8} + {}_{2}He^{4} \rightarrow {}_{2}He^{4} + {}_{2}He^{4} + {}_{2}He^{4}$$

Since $_{4}Be^{8}$ nucleus is unstable and readily breaks up to give two α-particles.

Nuclear Transmutation

(ii) (*p*, *n*) reactions : A (*p*, *n*) reaction, in general, can be expressed as

$$_{Z}X^{A} + {}_{1}H^{1} \rightarrow [{}_{Z+1}C^{A+1}] \rightarrow {}_{Z-1}Y^{A} + {}_{0}n^{1}$$

Obviously this type of transmutation produces a nucleus, which is one atomic number higher than the target nucleus X without changing its mass number. The particular examples of such reactions are :

$$_{5}B^{11} + {}_{1}H^{1} \rightarrow [{}_{6}C^{12}] \rightarrow {}_{6}C^{11} + {}_{0}n^{1}$$

$$_{8}O^{18} + {}_{1}H^{1} \rightarrow [{}_{9}F^{19}] \rightarrow {}_{9}F^{18} + {}_{0}n^{1}$$

$$_{28}Ni^{58} + {}_{1}H^{1} \rightarrow [{}_{29}Cu^{59}] \rightarrow {}_{29}Cu^{58} + {}_{0}n^{1}$$

$$_{29}Cu^{65} + {}_{1}H^{1} \rightarrow [{}_{30}Zn^{66}] \rightarrow {}_{30}Zn^{65} + {}_{0}n^{1}$$

All (*p*, *n*) reactions are *endoergic*.

Nuclear Transmutation

All (*p, n*) reactions are *endoergic*.

(iii) (*p*, γ) reactions : A (*p*, γ) reaction, in general, can be expressed as

$${}_{Z}X^{A} + {}_{1}H^{1} \rightarrow [{}_{Z+1}C^{A+1}] \rightarrow {}_{Z+1}Y^{A+1} + \gamma.$$

The type of transmutation produces a nucleus, which has atomic number and mass number both greater by 1 than those by target nucleus.

The specific examples are

$${}_{3}Li^{7} + {}_{1}H^{1} \rightarrow [{}_{4}Be^{8}] \rightarrow {}_{4}Be^{8} + \gamma$$

$${}_{9}F^{19} + {}_{1}H^{1} \rightarrow [{}_{10}Ne^{20}] \rightarrow {}_{10}Ne^{20} + \gamma$$

$${}_{13}A^{27} + {}_{1}H^{1} \rightarrow [{}_{14}Si^{28}] \rightarrow {}_{14}Si^{28} + \gamma$$

The reactions are exoergic and γ-ray photons produced are highly energic and can be used to induce nuclear disintegration.

Nuclear Transmutation

(iv) (*p*-*d*) reactions : A (*p*, *d*) reaction in general may be expressed as

$$_{Z}X^{A} + {}_{1}H^{1} \rightarrow [_{Z+1}C^{A+1}] \rightarrow {}_{Z+1}Y^{A-1} + {}_{1}H^{2}$$

This product nucleus *Y* has one mass number lower than that of target nucleus.

The specific examples are

$$_{4}Be^{9} + {}_{1}H^{1} \rightarrow [_{5}Be^{10}] \rightarrow {}_{4}Be^{8} + {}_{1}H^{2}$$

$$_{3}Li^{7} + {}_{1}H^{1} \rightarrow [_{4}Be^{8}] \rightarrow {}_{3}Li^{6} + {}_{1}H^{2}$$

(b) Deuteron-Induced Nuclear Reactions (*i.e.*, Transmutation by Deuterons) : Deuterons behave as effective projectiles for nuclear transmutations due to following reasons :

(i) The binding energy of deuteron is about 2 *MeV*, and the absorption of a neutron and a proton (constituents of a deuteron) adds net 14 *MeV* energy to a target nucleus which is sufficient to overcome to potential barrier of nucleus, thus forming the compound nucleus.

Nuclear Transmutation

(ii) When energy of incidence deuteron exceeds the deuteron binding energy, the deuteron breaks up into a neutron and a proton. The proton is repelled by positive charge of nucleus, while neutron is absorbed by nucleus, thus enhancing the probability of transmutation. The deuteron-induced nuclear reactions are of (d, α), (d, p) and (d, n) types.

(i) (d, α) reactions : A (d, α) reaction in general, may be expressed as

$$_{Z}X^{A} + {}_{1}H^{2} \rightarrow [{}_{Z+1}C^{A+1}] \rightarrow {}_{Z-1}Y^{A-2} + {}_{2}He^{4}$$

The specific examples are

$$_{3}Li^{6} + {}_{1}H^{2} \rightarrow [{}_{4}Be^{8}] \rightarrow {}_{2}He^{4} + {}_{2}He^{4}$$

$$_{8}O^{16} + {}_{1}H^{2} \rightarrow [{}_{9}F^{18}] \rightarrow {}_{7}N^{14} + {}_{2}He^{4}$$

$$_{13}Al^{27} + {}_{1}H^{2} \rightarrow [{}_{14}Si^{29}] \rightarrow {}_{12}Mg^{25} + {}_{2}He^{4}$$

All these reactions have positive Q-values.

Nuclear Transmutation

(ii) (*d*, *p*) reactions : A (*d*, *p*) reaction, in general, may be expressed as

$$_{Z}X^{A} + {}_{1}H^{2} \rightarrow [_{Z+1}C^{A+2}] \rightarrow {}_{Z}X^{A+1} + {}_{1}H^{1}$$

The specific example are

$$_{6}C^{12} + {}_{1}H^{2} \rightarrow [_{7}N^{14}] \rightarrow {}_{6}C^{13} + {}_{1}H^{1}$$

$$_{11}Na^{23} + {}_{1}H^{2} \rightarrow [_{12}Mg^{25}] \rightarrow {}_{11}Na^{24} + {}_{1}H^{1}$$

$$_{15}P^{31} + {}_{1}H^{2} \rightarrow [_{16}S^{33}] \rightarrow {}_{15}P^{32} + {}_{1}H^{1}$$

(iii) (*d*, *n*) reactions : A (*d*, *n*) reaction, in general may be expressed as

$$_{Z}X^{A} + {}_{1}H^{2} \rightarrow [_{Z+1}C^{A+2}] \rightarrow {}_{Z+1}Y^{A+1} + {}_{0}n^{1}$$

The specific example are

$$_{3}Li^{7} + {}_{1}H^{2} \rightarrow [_{4}Be^{9}] \rightarrow {}_{4}Be^{8} + {}_{0}n^{1}$$

$$_{4}Be^{9} + {}_{1}H^{2} \rightarrow [_{5}B^{11}] \rightarrow {}_{5}B^{10} + {}_{0}n^{1}$$

$$_{6}C^{12} + {}_{1}H^{2} \rightarrow [_{7}N^{14}] \rightarrow {}_{7}N^{13} + {}_{0}n^{1}$$

However, the most interesting examples of deuteron induced reactions are those in which target contains deuterons

(*d*, *p*) reactions, $_{1}H^{2} + {}_{1}H^{2} \rightarrow [_{2}He^{4}] \rightarrow {}_{1}H^{3} + {}_{1}H^{1}$

(*d*, *n*) reactions, $_{1}H^{2} + {}_{1}H^{2} \rightarrow [_{2}He^{4}] \rightarrow {}_{2}He^{3} + {}_{0}n^{1}$

Nuclear Transmutation

(c) α-particles Induced Reactions (*i.e.*, Transmutation by α-particles) :

The α-particles induced reactions are classified as

(α, *p*) and (α, *n*) reactions.

(i) **(α, *p*)** Reactions : A (α, *p*) reaction in general, may be expressed as

$$_{Z}X^{A} + {_2}He^{4} \rightarrow [_{Z+2}C^{A+4}] \rightarrow {_{Z+1}}Y^{A+3} + {_1}H^{1}$$

The specific examples are

$$_{7}N^{14} + {_2}He^{4} \rightarrow [_{9}F^{18}] \rightarrow {_8}O^{17} + {_1}H^{1}$$

$$_{13}Al^{27} + {_2}He^{4} \rightarrow [_{15}P^{31}] \rightarrow {_{14}}Si^{30} + {_1}H^{1}$$

$$_{16}S^{32} + {_2}He^{4} \rightarrow [_{18}A^{36}] \rightarrow {_{17}}Cl^{35} + {_1}H^{1}$$

$$_{19}K^{39} + {_2}He^{4} \rightarrow [_{21}Sc^{43}] \rightarrow {_{20}}Ca^{42} + {_1}H^{1}$$

$$_{21}Sc^{45} + {_2}He^{4} \rightarrow [_{23}V^{49}] \rightarrow {_{22}}Ti^{48} + {_1}H^{1}$$

Nuclear Transmutation

(ii) (α, n) reactions : A (α, n) reaction, in general, may be expresses as

$$_ZX^A + {}_2He^4 \rightarrow [_{Z+2}C^{A+4}] \rightarrow {}_{Z+2}Y^{A+3} + {}_0n^1$$

The specific examples are

$$_3Li^7 + {}_2He^4 \rightarrow [_5B^{11}] \rightarrow {}_5B^{10} + {}_0n^1$$

$$_4Be^9 + {}_2He^4 \rightarrow [_6C^{13}] \rightarrow {}_6C^{12} + {}_0n^1$$

$$_7N^{14} + {}_2He^4 \rightarrow [_9F^{18}] \rightarrow {}_9F^{17} + {}_0n^1$$

$$_{13}Al^{27} + {}_2He^4 \rightarrow [_{15}P^{31}] \rightarrow {}_{15}P^{30} + {}_0n^1$$

The second of these reactions led to the discovery of **neutron**.

Nuclear Transmutation

(d) Neutrons induced reactions (*i.e.,* Transmutation by neutrons) : The neutrons are effective projectiles for nuclear transmutation than charged particles because they are neutral and hence they are not repelled by positive nucleus. The neutrons induced reactions are classified as (n, α), (n, p), (n, γ) and $(n, 2n)$ reactions.

(i) (n, α) reactions : A (n, α) reaction, in general may be expressed as

$$_{Z}X^{A} + {_0}n^{1} \rightarrow [_{Z}C^{A+1}] \rightarrow {_{Z-2}}Y^{A-3} + {_2}He^{4}$$

The specific examples are

$$_{6}Li^{6} + {_0}n^{1} \rightarrow [_{3}Li^{7}] \rightarrow {_1}H^{3} + {_2}He^{4}$$

$$_{5}B^{10} + {_0}n^{1} \rightarrow [_{5}B^{11}] \rightarrow {_3}Li^{7} + {_2}He^{4}$$

$$_{13}A^{27} + {_0}n^{1} \rightarrow [_{13}A^{28}] \rightarrow {_{11}}Na^{24} + {_2}He^{4}$$

(ii) (n, p) reactions : A (n, p) reaction, in general, may be expressed as

$$_{Z}X^{A} + {_0}n^{1} \rightarrow [_{Z}C^{A+1}] \rightarrow {_{Z-1}}Y^{A} + {_1}H^{1}$$

The specific examples are

$$_{7}N^{14} + {_0}n^{1} \rightarrow [_{7}N^{15}] \rightarrow {_6}C^{14} + {_1}H^{1}$$

$$_{13}Al^{27} + {_0}n^{1} \rightarrow [_{13}Al^{28}] \rightarrow {_{12}}Mg^{27} + {_1}H^{1}$$

$$_{30}Zn^{64} + {_0}n^{1} \rightarrow [_{30}Zn^{65}] \rightarrow {_{29}}Cu^{64} + {_1}H^{1}$$

Nuclear Transmutation

(iii) (n, γ) reactions : The nuclei of most elements other than very lightest capture the slow neutrons. This process is called *radiative capture*. The product nucleus, due to addition of about 8 *MeV* energy, is in excited state and emits γ-rays. Thus, the product nucleus is an isotope for target nucleus, with a mass number, one unit greater.

A (n, γ) reaction, in general may be expressed as

$$_ZX^A + {}_0n^1 \rightarrow [{}_ZC^{A+1}] \rightarrow {}_ZX^{A+1} + \gamma$$

The specific examples are

$$_{13}Al^{27} + {}_0n^1 \rightarrow [{}_{13}Al^{28}] \rightarrow {}_{13}Al^{28} + \gamma$$

$$_{49}In^{115} + {}_0n^1 \rightarrow [{}_{49}In^{116}] \rightarrow {}_{49}In^{116} + \gamma$$

$$_{92}U^{238} + {}_0n^1 \rightarrow [{}_{92}U^{239}] \rightarrow {}_{92}U^{239} + \gamma$$

Nuclear Transmutation

(iv) (*n*, 2*n*) reactions : In these reactions the target nucleus captures one neutron and the compound nucleus, so formed, emits two neutrons. A (*n*, 2*n*) reaction, in general, may be expressed as

$$_{Z}X^{A} + {}_{0}n^{1} \rightarrow [{}_{Z}C^{A+1}] \rightarrow {}_{Z}X^{A-1} + {}_{0}n^{1} + {}_{0}n^{1}$$

The specific examples are

$$_{13}Al^{27} + {}_{0}n^{1} \rightarrow [{}_{13}Al^{28}] \rightarrow {}_{13}Al^{26} + {}_{0}n^{1} + {}_{0}n^{1}$$

$$_{92}U^{238} + {}_{0}n^{1} \rightarrow [{}_{92}U^{239}] \rightarrow {}_{92}U^{237} + {}_{0}n^{1} + {}_{0}n^{1}$$

The *Q*-value of (*n*, 2*n*) reactions is always negative and hence is produced only by fast neutrons.

Nuclear Transmutation

(e) Photon-induced Nuclear Reactions (*i.e.*, Transmutation by photons) : If a photon has energy greater than the binding energy of target nucleus, it can produce nuclear transmutation. This process is called photo-disintegration or photo-nuclear reaction.

For photo disintegration the energy of incident photon is of the order of 10 MeV. Therefore such reactions are *endoergic*.

The specific examples are

$$_{15}P^{31} + \gamma \rightarrow [_{15}P^{31}] \rightarrow {}_{15}P^{30} + {}_{0}n^{1}$$

$$_{13}Al^{27} + \gamma \rightarrow [_{13}Al^{27}] \rightarrow {}_{13}Al^{26} + {}_{0}n^{1}$$

The following reactions can occur with low energies of incident photon due to low binding energies of target nuclei.

$$_{1}H^{2} + \gamma \rightarrow [_{1}H^{2}] \rightarrow {}_{1}H^{1} + {}_{0}n^{1}$$

$$_{4}Be^{9} + \gamma \rightarrow [_{4}Be^{9}] \rightarrow {}_{4}Be^{8} + {}_{0}n^{1}$$

These are examples of (γ, n) reactions. Another type of photo-disintegration reactions for low photon-energies are (γ, p) reactions. But for higher energies of incident photons, the reactions (γ, np), $(\gamma, 2n)$, $(\gamma, n2p)$, (γ, α) may also occur.

Nuclear Transmutation

SOLVED EXAMPLE

Ex. 1. *Find the Q-value of the following reaction*

$$_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1H^1 + Q$$

The atomic masses of reactions and products are

$_7N^{14} = 14 \cdot 00755\ u$, $_2He^4 = 4 \cdot 00388\ u$

$_8O^{17} = 17 \cdot 00453\ u$ *and* $_1H^1 = 1 \cdot 00815\ u$ *(Rajasthan 1998)*

Sol. The Q-value of reaction is $\Delta m . c^2$

$$Q = [({}_7N^{14} + {}_2He^4) - ({}_8O^{17} + {}_1H^1)]\ c^2$$

$$= [(14 \cdot 00755 + 4 \cdot 00388) - (17 \cdot 00453 + 1 \cdot 00815)]\ u$$

$$= [8 \cdot 01143 - 18 \cdot 01268]\ u = -0 \cdot 00125\ u$$

But $1\ u = 931\ MeV$

$\therefore$ $Q = -0 \cdot 00125 \times 931 = -$ **1·16 MeV**

That is Q-value is negative and so that reaction is *endothermic*.

Nuclear Transmutation

Ex. 2. *Calculate the energy generated in kWh when* $0 \cdot 1$ *kg of* $_3Li^7$ *is converted into* $_2He^4$ *by proton-bombardment.*

The atomic masses are $_3Li^7 = 7 \cdot 0183\ u$, $_2He^4 = 4 \cdot 0040\ u$

$_1H^1 = 1 \cdot 0081\ u$ *(Delhi 1997)*

Sol. The reaction is

$$_3N^7 + {}_1H^1 \rightarrow 2({}_2He^4)] + Q$$

The *mass defect*,

$$\Delta m = [({}_3Li^7 + {}_1H^1)] - 2({}_2He^4)$$

$$= 7 \cdot 0183 + 1 \cdot 0081 - 2 \times 4 \cdot 0040$$

$$= 0 \cdot 0184\ u$$

$\therefore$ Energy released $Q = [0 \cdot 0184\ u]$

$$= 0 \cdot 0184 \times 931\ MeV = \mathbf{17 \cdot 13\ MeV}$$

$$= 17 \cdot 13 \times 1 \cdot 6 \times 10^{-13}\ \text{joule}$$

$$= 27 \cdot 408 \times 10^{-13}\ \text{joule}$$

Mass of $_3Li^7 = 7 \cdot 0183\ u$

$$= \frac{7 \cdot 0183}{6 \cdot 02 \times 10^{26}}\ \text{kg} = 1 \cdot 176 \times 10^{-26}\ \text{kg}$$

$\therefore$ Heat generated by $1 \cdot 176 \times 10^{-26}$ kg of $_3Li^7 = 27 \cdot 408 \times 10^{-13}$ J

$\therefore$ Heat generated by $0 \cdot 1$ kg of Li^7

$$= \frac{27 \cdot 408 \times 10^{-13} \times 0 \cdot 1}{1 \cdot 176 \times 10^{-26}} = 2 \cdot 33 \times 10^{13}\ \text{Joule}$$

$$= \frac{2 \cdot 33 \times 10^{13}}{1000 \times 3600}\ \text{kWh} = \mathbf{6 \cdot 47 \times 10^7\ kWh}.$$

Nuclear Transmutation

Ex. 3. *The Q-value of* Na^{23} $(n\alpha)$ F^{20} *reaction is* $-5 \cdot 4$ *MeV. Determine the threshold energy of the neutrons for this reaction.*

Given mass of ${}_0n^1 = 1 \cdot 008665\ u$

mass of $Na^{23} = 22 \cdot 9898\ u$

Sol. $Q = -5 \cdot 4 \text{ MeV}, m_a = m_n = 1 \cdot 008665 \text{ u}$

$$M_X = M_{Na} = 22 \cdot 9898 \text{ u}$$

$$\therefore \quad E_{th} = -Q\left(\frac{M_a + M_X}{M_X}\right) = -(5 \cdot 4)\,\frac{(1 \cdot 008665 + 22 \cdot 9898)}{22 \cdot 9898}\ MeV$$

$$= \mathbf{5 \cdot 635\ MeV}$$

Nuclear Transmutation

Ex. 4. *Calculate the threshold energy required to initiate the reaction* $P^{31}(n, p)Si^{31}$. *Given that*

$$p = 1\cdot00814\ u,\ n = 1\cdot00898\ u$$

$$P^{31} = 30\cdot98356\ u,\ S^{31} = 30\cdot98515\ u$$ *(Osmania University. 2008, 1994)*

Sol. Threshold energy for nuclear reaction $a + X = Y + b$ is

$$E_{th} = -Q\left[\frac{M_a + M_X}{M_X}\right]$$

where

$$Q = [(M_a + M_X) - M_b + M_Y)]c^2$$

$$= [\{M(n) + M(P^{31})\} - \{M(p) + M\ (Si)\}]c^2 \text{ joule}$$

$$= [\{M(n) + M(P^{31})\} - \{M(p) + M(Si^{31})\}]\ u$$

$$= [(1\cdot00898 + 30\cdot98356) - (1\cdot00814 + 30\cdot98515)]\ u$$

$$= (31\cdot99254 - 31\cdot99329) \times 931\ MeV (\because 1\ u = 931\ MeV)$$

$$= -0\cdot00075 \times 931\ MeV = -0\cdot69825\ MeV$$

∴ **Threshold energy,**

$$E_{th} = -Q\frac{M_n + M\ (P^{31})}{M\ (P^{31})}$$

$$= -(-0\cdot69825\ MeV).\left(\frac{1\cdot00898 + 30\cdot98356}{30\cdot98356}\right)$$

$$= 0\cdot69825 \times \frac{31\cdot99254}{30\cdot98356}\ MeV = 0\cdot721\ MeV$$