CHAPTER 20

NUCLEAR PHYSICS

ATOMIC NUCLEUS

→ Protons and neutrons are collectively called as neucleons.

→ Z : Atomic Number

A : Atomic Mass

No. of Neutrons = A − Z

→ A nuclide is a particular nucleus with a specified number of protons and neutrons.

Represented by $_{Z}X^{A}$

→ Charge on Nucleus = Ze

* Nuclear Size ≈ 10^{-14} m

Mass of nucleus ≈ 10^{-27} kg

ISOTOPES

→ Atoms of an element which has the same atomic number Z, but have different mass number A, are referred to as isotopes.

→ Isotopes have different number of neutrons.

→ Chemical properties are same for isotopes, bcz chemical reaction depends on number of electrons.

MASS SPECTOGRAPH

→ It is a device with the help of which not only the isotopes of any element can be separated from one another but their masses can also be determined quite accurately.

* PRINCIPLE : A beam of ions moving through electric and magnetic fields suffers a deflection that depend upon the charge and masses of the ions.

$$r = \sqrt{\frac{2Vm}{B^2q}}$$

$$r \propto \sqrt{m}$$

NUCLEAR MASSES

→ One mass unit, called an atomic mass unit or a.m.u is equal to 1/12 of the mass of carbon atom $_6C^{12}$.

$1\ amu = 1.6 \times 10^{-27}\ kg$

$1\ amu = 1.49 \times 10^{-10}\ J$

$1\ u = 931\ MeV$

$1\ eV = 1.6 \times 10^{-19}\ J$

* Mass of electron:

→ $9 \times 10^{-31}\ kg$

→ $5.4 \times 10^{-4}\ u$

→ $0.51\ MeV$

* Mass of Proton:

→ $1.67 \times 10^{-27}\ kg$

→ $1.007\ u$

→ $937\ MeV$

* Mass of Neutron:

→ $1.67 \times 10^{-27}\ kg$

→ $1.008\ u$

→ $938\ MeV$

MASS DEFECT AND BINDING ENERGY

→ The work needed to separate a nucleus into separate neutrons and protons is referred to as the binding energy of the nucleus.

→ The mass of a nucleus is less than the mass of the same number of separate neutrons and protons.

→ The mass of a helium nucleus having 2 protons and 2 neutrons is 0.8% less than the same number of protons and neutrons.

This difference is called the mass defect of the nucleus and is due to the protons and neutrons binding together when the nucleus is formed.

→ This 'missing mass' is known as the mass defect, and represents the energy that was released when the nucleus was formed.

→ As $E = mc^2$

so, Binding Energy = mass defect × c^2

→ Nuclear masses are usually expressed in amu.

BINDING FACTOR:

→ Binding energy per nucleon (i-e protons and neutrons) is called binding factor

* Binding Factor, $f = \frac{B.E}{A}$

→ It is used to measure stability of nucleus.

* Steps of Finding Binding Factor:

(1) Find mass defect of the nucleus (in amu)

$\Delta m =$ (mass of individual protons + neutrons) − Total mass

(2) Find binding energy E_b (in MeV)

$E_b = 931 \times \Delta m c^2$

As $1u = 931$ MeV

(3) Find Binding Factor

$f = \frac{E_b}{A}$

* Atomic Mass > 80 = Fission Reaction
  Atomic Mass < 50 = Fusion Reaction
  Atomic Mass from 50-80 = Highly stable

* For Radioactivity :
  Atomic Number > 82

RADIOACTIVITY

→ Radioactivity discovered by Henry Becquerel when he was conducting research into the effects of X-rays.

→ Marie Curie and her husband Pierre discovered Radium and Polonium.

→ The phenomenon of the spontaneous distintegration of heavier elements Z > 82 in to lighter elements along with the emission of three types of radiations is called radioactivity

1. ALPHA PARTICLES ($_2He^4$)

→ consist of two protons and two neutrons.

→ positively charged helium nuclei

→ emitted by a very large unstable nucleus

→ easily stopped by cardboard or thin metal

→ has a range in air of no more than a few cm.

→ ionizes air molecules much more strongly than other two types

2. BETA PARTICLES

→ β particles consist of electrons
→ emitted when a nucleus with too many neutrons disintegrates
→ A neutron in such a nucleus suddenly and unexpectedly changes to a proton; in the process, an electron is created and instantly emitted from the nucleus.

* β - Particles:
→ stopped by 5 - 10 mm of metal
→ range in air of about 1m
→ ionizes air molecules less strongly than α - particles

3. GAMMA RADIATIONS

→ consist of high energy photons
→ A gamma photon is emitted from a nucleus with surplus energy after it has emitted an α or β - particle
→ stopped only be several cm of lead
→ infinite range in air
→ ionizes air molecules very weakly

* Radioactive elements disintegrates and emit α, β and γ radiations. This process is called transmutation by spontaneous disintegration.

ALPHA EMISSION

$$_{Z}X^{A} \rightarrow {}_{Z-2}Y^{A-4} + {}_{2}He^{4} + Q$$

- → Atomic Number reduces by 2
- → Mass Number reduces by 4
- → Q : disintegration energy and is always positive, as the process is spontaneous.
- → $_{Z}X^{A}$: parent nucleus
- → $_{Z-2}Y^{A-4}$: daughter nucleus

→ The daughter nucleus may also remain unstable and undergo further disintegration till it attains stability.

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

$$_{88}Ra^{226} \rightarrow {}_{86}Rn^{222} + {}_{2}He^{4} + Q$$

* α- Particle is about 7000 times more massive than an electron

BETA EMISSION

- → no change in mass number
- → change in atomic number by −1 or +1
- → If negative β- particle (electron) is emitted then change in Z is +1

$$_{Z}X^{A} \longrightarrow {}_{Z+1}X^{A} + {}_{-1}\beta^{0} + \text{antineutrino} + Q,$$

- → If positive β- particle (positron) is emitted then change in Z is −1

$$_{Z}X^{A} \longrightarrow {}_{Z-1}X^{A} + {}_{+1}\beta^{0} + \text{Neutrino} + Q,$$

- → A neutrino is a fermion that interacts only via the weak subatomic force and gravity. The mass of neutrino is much smaller than that of other known elementary particles.

$$_{90}Th^{234} \longrightarrow {}_{91}Pa^{234} + {}_{-1}\beta^{0} + \text{Antineutrino} + Q.$$

Thorium → Protactinium

$$_{0}n^{1} \longrightarrow {}_{1}H^{1} + {}_{-1}\beta^{0} + \text{Antineutrino}$$

Neutron in free space → Proton

$$_{6}C^{14} \longrightarrow {}_{7}N^{14} + {}_{-1}\beta^{0} + \text{Antineutrino}$$

$$_{6}C^{11} \longrightarrow {}_{5}B^{11} + {}_{1}\beta^{0} + \text{Neutrino}$$

GAMMA EMISSION

→ Most frequently the alpha or beta emission leaves the daughter nuclide in an excited state. Such a nuclide may go back to a more ~~more~~ stable configuration and eventually to its ground state by emitting one or more γ- rays.

→ No change in mass number (A)

→ No change in atomic number (Z)

$$_{Z}X^{A} \longrightarrow (_{Z}X^{A})^{*} \longrightarrow {}_{Z}X^{A} + \gamma$$

$(_{Z}X^{A})^{*}$ represent excited state of nucleus

HALF - LIFE

The half-life of a radioactive isotope is the time taken for half the number of isotope to disintegrate.

Half Life of :

1. Neutron → 12 min
2. Polonium 212 → 3×10^{-7} s
3. Lead 204 → 1.4×10^{7} Years
4. Carbon 14 → 5730 Years
5. U^{238} → 4.5×10^{9} Years
6. DDT → 10 - 15 Years

* $\frac{\Delta N}{\Delta t} = -\lambda N$

$\Delta N/\Delta t$: Rate of Decay

N : No. of undecayed nuclei

λ : Decay constant

* RADIO ACTIVE DECAY LAW :

This law states that the rate of decay is directly proportional to the number of undecayed nuclei present at that time.

* Decay constant (λ) depends on nature of element and determines the rate at which an isotope will decay.

* Isotopes with large value of λ decay at rapid rate while those with small λ value decay slowly.

* The Decay Rate or Activity of a sample is defined as the number of decay per second.

$$R = -\frac{\Delta N}{\Delta t} = \lambda N$$

* $N = N_0 e^{-\lambda t}$

N : No. of radioactive nuclei present at time t

N_0 : number present at time $t = 0$

$e = 2.718$

* Unit of Activity : Curie

SI Unit of Activity : Becquerel

* $1 \text{ Ci} = 3.7 \times 10^{10}$ decay/s

1 Bq = 1 decay per second

* Approximate activity of 1g of Radium = 1 Ci i-e 3.7×10^{10} decay/second

* Relation Between $T_{1/2}$ and λ

$$T_{1/2} = \frac{0.693}{\lambda}$$

→ The rate of radioactive decay is directly proportional to the stability of the isotope.

Time	Undecayed	Decayed
0 sec	N_0 (100%)	zero 0%
1 $T_{1/2}$	$N_0/2$ (50%)	$N_0/2$ (50%)
2 $T_{1/2}$	$N_0/4$ (25%)	$N_0 - \frac{N_0}{4} = 3N_0/4$ (75%)
3 $T_{1/2}$	$N_0/8$ (12.5%)	$7N_0/8$ (87.5%)
4 $T_{1/2}$	$N_0/16$ (6.25%)	$15N_0/16$ (93.75%)

* FOR UNDECAYED NUCLEI :

$$N = \frac{N_0}{2^n}$$

n : no. of half lives passed
N_0 : initial no. of undecayed nuclei

* For DECAYED NUCLEI :

$$N = N_0 - \frac{N_0}{2^n}$$

INTERACTION OF RADIATION WITH MATTER

→ Ionization is the main interaction with matter to detect the particle or to measure its energy.

→ The ionization may be due to direct elastic collisions or through electrostatic attraction.

→ The range of a particle depends on:

1. Charge, mass and energy of particle
2. Density of medium and ionization potentials of the atoms of the medium.

→ α-particle continues producing intense ionization along its straight path till it loses all its energy and comes almost to rest. It then captures two electrons from the medium and become a neutral helium atom.

→ The ionization ability of β-particles is about 100 times less than that of α-particles.

→ The range of β-particles is about 100 times more than α-particles.

→ The path of β-particle in matter is not straight but shows much straggling or scattering.

→ The range of β- particles is measured by the effective depth of penetration into the medium; not by length of erratic path. If the density of the material is more through which the particle moves, the shorter will be its range.

→ α and β- particles both radiate energy as X-rays photons when they are slowed down by the electric field of the charged particles in a solid material.

→ Photons of γ-rays, being uncharged, cause very little ionization.
Photons are removed from a beam by either scattering or absorption in the medium.

→ γ-rays interact with matter in three distinct ways, depending mainly on their energy

1. At energy < 0.5 MeV → Photoelectric effect

2. At intermediate energies i.e 1 MeV → Compton scattering
3. At energy > 1.02 MeV → Pair Production

→ In air, γ-rays intensity falls off as the inverse square of the distance from the source.

$$I \propto \frac{1}{d^2}$$

→ In solids, the intensity of γ-rays decreases exponentially with increasing depth of penetration into the material.

→ The intensity I_0 of a beam of photon after passing through a distance x in the medium is reduced to intensity I given by the relation:

$$I = I_0 e^{-\mu x}$$

μ: linear absorption co-efficient of the medium

μ depends on energy of photon as well as on properties of matter.

→ Charged particles α or β or γ-radiation produce fluorescence or glow or on striking some substance like zinc sulphide, sodium iodide or barium platinocyanide coated screens.

* Fluorescence:

Fluorescence is the property of absorbing radiant energy of high frequency and re emitting energy of low frequency in the visible region of electromagnetic Spectrum.

→ Neutrons, being neutral particles, are extremely penetrating particles.

→ To be stopped or slowed, a neutron must undergo a direct collision with a nucleus or some other particles that has mass comparable to that of neutron.

→ Materials such as water or plastic, which contain more low mass nuclei per unit volume are used to stop neutrons.

→ Neutrons produce a little indirect ionization when they interact with materials containing H- atoms and knock out protons.

RADIATION DETECTORS

1. Geiger- Muller Counter
2. Solid state Detector
3. Wilson Cloud Chamber

1. GEIGER- MULLER COUNTER

Working Principle:

A Geiger meter passes radioactive elements through an inert gas inside the machine. Due to their polar nature, radioactive particles ionize the gas they are dispersed in. The resulting ions can be easily detected relative to radioactivity itself.

Setup:

1. Window:

A Geiger counter is a metal cylinder sealed in by a ceramic or mica window at one end to allow the radioactive particles in the surroundings to permeate it easily.

2. ANODE (Metal wire)

Running down the tube is a thin metal wire, usually composed of tungsten.

The wire is ~~xx~~ maintained at a high positive potential (about 1000V) w.r.t the tube.

3. CATHODE

The curved surface of the matal tube act as negative electrode- the cathode.

WORKING :-

The cylinder is filled with an inert gas such as Neon or Argon. As radioactive particles pass through, they ionize this gas. Positive and negative ions move towards respective electrodes.

Moreover, as the electrons move down the gas, they collide into more atoms, causing a chain reaction of ionization that produces more ions and electrons. This is called Geiger discharge.

Subsequently, many electrons will arrive at the anode, generating a pulse of electricity that is measured on a meter.

Each pulse from the tube is calibrated to a count. Counts per Second give an approximation of the strength of the radiation field.

2. SOLID STATE DETECTOR

→ Also called semi-conductor diode detector

→ A P-N junction operated under reverse bias

→ As an energetic particle passes through the junction, electrons and holes are created.

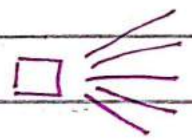
→ Electrons and holes move towards opposite poles and create a pulse of current that can be measured with any electronic counter.

→ In a typical device, the duration of the pulse is about 10^{-7} s.

3. WILSON CLOUD CHAMBER

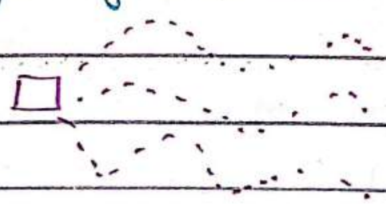
* α- Particle Source

If a substance placed in Wilson cloud chamber emit straigh lines, it is an α- Particle source.



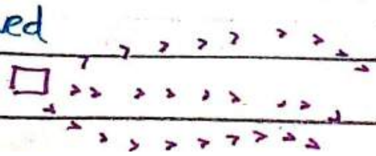
* β- Source

zig-zag broken lines are observed



* γ- Source

Small sparks (sentillations) are observed



NUCLEAR REACTIONS

→ Such collisions, which change the identity or properties of the target nuclei, are called nuclear reactions.

These laws are conserved in nuclear reactions:

1. Conservation of Atomic and mass number
2. Conservation of mass-energy.

1. NUCLEAR FISSION

"The process of splitting a heavy nucleus into two lighter nuclei is called nuclear fission"

→ Only U^{235} undergo fission - though naturally occuring uranium has 99.3% of U^{238} and 0.7% of U^{235}.

$${}_0n^1 + {}_{92}U^{235} \longrightarrow {}_{92}U^{*236} \longrightarrow {}_{36}Kr^{92} + {}_{56}Ba^{141} + 3\,{}_0n^1 + Q$$

→ When one thermal neutron strikes a uranium nuclei, three neutrons are emitted.

→ Q is the energy of reaction which can be calculated from the value of rest masses of different nuclei.

$$Q = \Delta m \times 931\ MeV$$

where Δm = Initial mass - Final mass

→ When one atom of U^{235} undergoes fission 200 MeV of energy is released.

→ 1 kg of uranium deliver as much energy as the combustion of about 3000 tons of coal.

FISSION CHAIN REACTION

→ If fission chain reaction is not controlled, the large energy can cause a violent explosion and destroy everything that comes in its way. This is the principle of atom bomb.

→ For the chain reaction to start, it is necessary that the mass of uranium must be greater than some minimum mass called the critical mass or critical size.

* To Find Number of Neutrons in Fission Process:

No. of neutrons = 3^n

e.g

At second step = 3^2 = 9 neutrons

* For Single Fission.

Time = 0.01 sec

No. of fissions in 1 sec = 100

NUCLEAR REACTORS

→ used to produce power, to supply neutrons, to produce radio isotopes.

* Construction:

It consist of 5 parts

1. A core of nuclear fuel
2. A moderator for slowing down neutrons
3. Control rods
4. Coolant or heat exchanger for removing heat in the core
5. Radiation shielding

1. NUCLEAR FUEL

→ U^{233}, U^{235} or Pu^{239} are used

→ When natural uranium is used, plutonium is produced in the nuclear reactor.

→ Usually the fuel is put in different aluminium cans in cylindrical rods placed some distance apart.

2. MODERATOR

→ small pieces of ~~[illegible]~~ materials which are capable of slowing down neutrons to thermal energies, so that they can cause fission in other nuclei.

→ The material of ~~mater~~ moderator should be light and shouldnot absorb neutrons.

→ Usually, graphite and heavy water (water containing deutrium instead of hydrogen) are used as moderators.

3. CONTROL RODS

→ consist of a material that absorbs neutrons e.g cadmium, boron or hafnium. Usually cadmium control rods are used

→ can be inserted into or drawn out of the reactor fuel core.

4. COOLANT OR HEAT EXCHANGER

→ used to cool the fuel rods and the moderator, and is capable of carrying away large amount of heat generated in the fission process.

→ If the moderator, fuel rods etc are not cooled, the heat generated can melt them.

→ The heat carried by the coolant produces steam ~~an~~ that can run a turbine, which in turn can run an electric generator.

5. RADIATION SHIELDING

→ To shield the harmful radiation emitted, a concrete wall which is a few feet thick is used to absorb these radiations.

Types Of Reactors

1. Thermal Reactors

→ Neutrons are slowed down to thermal energies.

→ Use natural uranium or slightly enriched uranium

→ Enriched uranium contains a greater percentage of U^{235} than natural uranium does.

→ Pressurized water reactor (PWR) are most widely used.

→ In PWR, water is prevented from boiling, being kept under high pressure. This hot water is used to boil another circuit of water which produces steam for turbine rotation of electricity generators.

2. Fast Reactor

→ make use of ${}_{92}U^{238}$

→ Each ${}_{92}U^{238}$ absorb fast neutron and change into ${}_{94}Pu^{239}$

$$ {}_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{93}Np^{239} + {}_{-1}\beta^{0} $$

$$ {}_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + {}_{-1}\beta^{0} $$

→ Plutonium can be fissioned by fast neutrons, hence moderator is not needed.

→ The core consist of a mixture of plutonium and uranium dioxide.

NUCLEAR FUSION

→ When two light nuclei combine to form a heavier nucleus, the process is called nuclear fusion.

→ In fusion reaction the mass of the final nucleus is less than the rest masses of the original nuclei, so there is a loss of mass accompanied by a release of energy.

→ The basic exothermic reaction in stars, including sun – is the fusion of hydrogen nuclei into helium nucleus.

→ This can take place in two different series :

1. Proton-proton cycle
2. Carbon cycle

* PROTON - PROTON CYCLE:

direct collision of protons result in the formation of heavier nuclei whose collision in turn yield helium nuclei.

$${}_1H^1 + {}_1H^1 \longrightarrow {}_1H^2 + \beta^+ + \nu$$

$${}_1H^2 + {}_1H^1 \rightarrow {}_2H^3 + \gamma$$

$${}_2H^3 + {}_1H^1 \rightarrow {}_2H^4 + \beta^+ + \nu$$

"ν" is called neutrino

→ Energy Yield of Proton-proton cycle is 24.7 MeV

→ In this cycle, 4 protons yield 1 α-particle.

* CARBON CYCLE:

→ The net result of carbon cycle is the formation of an α-particle and two positrons from four protons, with the evolution of 24.7 MeV.
The initial $_6C^{12}$ acts as a catalyst for the process, since it reappears at the end.

→ Fusion Reactions occur only under conditions of extreme temperature and pressure.
→ The interior temp of sun is estimated to be 2×10^6 K
→ In sun, the proton-proton and carbon cycles have about equal probabilities for occurance.
→ In general, carbon cycle is more efficient at high temperature.
Proton-proton cycle is more efficient at low temp
→ The energy librated in fusion reaction is often called thermonuclear energy.

RADIATION EXPOSURE

BackGround Radiation:

Back ground radiation is a measure of the level of ionizing radiation present in the environment at a particular location which is not due to deliberate introduction of radiation sources.

It is partly due to cosmic radiation which comes to us from outer space and partly from naturally occuring radioactive substance in the Earth's crust.

The cosmic radiation consists of highly energy charged particles and electromagnetic radiation.

* FOOD:

Most common radio active isotopes in food are K^{40} and C^{14}.

* RADIATIONS:

→ X-Rays exposures

→ radioactive waste from nuclear facilities, hospital, research and industrial establishments, colour televesion, luminous watches, tobbacco leaves

BIOLOGICAL EFFECTS OF RADIATION

→ damage to living tissues, cells, or organism
→ may cause death of individual cells
→ produce chromosome abnormalities
→ genetic mutation
→ Skin burns
→ loss of hair
→ drop in WBCs
→ induction of cancer

(Skin burns, loss of hair, drop in WBCs, induction of cancer: Somatic Effects)

→ Genetic Effects

BIOLOGICAL AND MEDICAL USES

→ Tracer techniques to find the process of photosynthesis and the incorporation of carbon atoms in the CO_2 into giant and complex protein or carbohydrate molecule.
→ Distribution of various elements in the body found through tracer technique.
→ Genetic mutations are engineered by intense radioactivity.
→ intentional selective destruction of tissues, such as cancerous tumor.
→ Co^{60} which emit β-particle and high energy γ-rays used for treatment of various type of cance.
→ Cancerous thyroid treated with I^{131} radio isotope.
→ I-131 is artificially produced isotope of iodine.
→ Radio active sodium used to find the presence or absence of constriction in the circulatory system

BASIC FORCES OF NATURE

Four Fundamental Forces

(1.) Strong (2) Electromagnetic

(3) Weak (4) Gravitational

1. STRONG FORCE

→ very short range (separation upto 10^{-14} m)

→ for binding of protons and neutrons in nuclei

→ strongest of all fundamental forces

2. ELECTROMAGNETIC FORCE

→ 10^{-2} times ($1/100^{th}$) the strength of strong force

→ for binding of atoms and molecules

→ long range force

$$F \propto \frac{1}{r^2}$$

3. WEAK FORCE

→ short-range nuclear force

→ tends to produce instability in certain nuclei

→ responsible for most radioactive decay processes such as β decay

→ ~~10 times~~

→ 10^{-9} times the strength of strong force

Weak and electromagnetic forces are two manifestations of a single force called electro weak force

4. GRAVITATIONAL FORCE

- → long-range force
- → 10^{-38} times strength of strong force
- → effect on elementary particles is negligible
- → weakest of all forces

FIELD PARTICLES OR QUANTA

Force	Field Particles
1. Electromagnetic induction (force) →	Photons
2. Strong Force →	Gluons
3. Weak Force →	W and z bosons
4. Gravitational Force →	Gravitons

CLASSIFICATION OF PARTICLES

1. HADRONS

→ Particles that interact through strong force
→ Two classes:

(a) Mesons (b) Baryons

(a) Mesons:

→ mass b.w mass of electron and mass of proton
→ Mesons are known to decay finally into electrons, positrons, neutrinos and photons.
→ Pion is the lightest of known mesons

(b) Baryons:

→ mass equal to or greater than proton mass
→ include protons and neutrons
→ All baryons decay into protons

2. LEPTONS

→ Particles that participate in weak interaction
→ include electrons, muon, and neutrinos
→ All leptons are less massive than lightest hadron.
→ has no internal structure so true elementary particles
→ Total six leptons

* Charged Leptons: electron, muon, tau
* Neutral Leptons: electron neutrino, muon neutrino, tau neutrino

3. QUARKS

- Quarks are the basic building blocks of mesons and baryons
- Six different types:
  up, down, strange, charmed, bottom, top
- For every quark, there is corresponding antiquark
- Quarks combine in three to form particles like protons and neutrons
- Anti quarks combine in three to form antiparticles like antiproton and antineutron
- A meson consist of a quark and an antiquark

Charge on Quarks

- u, c, t quarks carry charge $+\frac{2}{3}e$

  TUC $= +\frac{2}{3}e$

- d, s, b carry charge of $-\frac{1}{3}e$

- Antiquark carries an equal and opposite charge to its corresponding quark

Proton: Two up quarks, 1 down quark

Neutron: 1 up quark, 2 down quarks