Part I- Nuclear Physics (AY: 2021-22)

A. Introduction to Nuclear Physics:

1. ***Terminology***

1.1 (Atomic Number, Atomic Mass Number, Isotopes, Isobars, Isotones)

A given atom is specified by the number of

-neutrons: N

-protons: Z

-electrons: there are Z electron in neutral atoms

The atomic mass number (A) = Z + N
Atoms of the same element have same atomic number Z.

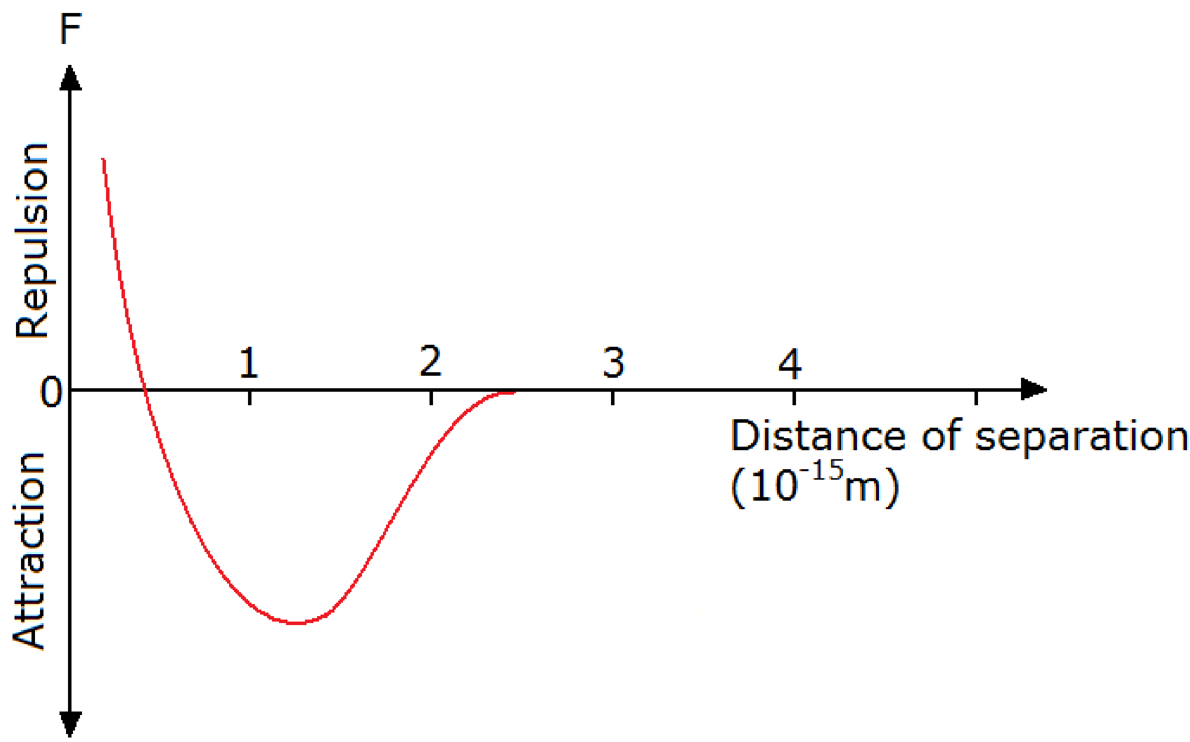
Isotopes: Isotopes of the same element have different number of neutrons N. Hence, isotopes have same atomic number (Z) but different atomic mass number (A). Example: $_{11}Na^{22}$ and $_{11}Na^{23}$
Isotones: Isotones are the elements having same number of neutrons (N) but with different number of protons (different Z) and therefore different atomic mass number (A). Example: $_{6}C^{14}$ and $_{7}N^{15}$
Isobars: Isobars are the elements having same atomic mass number (A) but with different atomic number (Z). Example: $_{6}C^{14}$ and $_{7}N^{14}$
Mirror nuclei: Two isobars with proton and neutron number interchanged i.e., the number of protons in one is equal to the number of neutrons in the other, are called mirror nuclei.

1.2 (Nuclear force and its characteristics)

Nuclear Force: The forces between nucleons, i.e., between proton and neutron, neutron and neutron are referred to as nuclear forces.

Characteristics of nuclear force:
1. The nuclear force is the strongest among the four basic forces or interactions found in nature.
2. The nuclear force is powerfully attractive between nucleons at distances of about 1 femtometre (fm, or 1.0×10^{-15} metres), but it rapidly decreases to insignificance at distances beyond about 2.5 fm. At distances less than 0.7 fm, the nuclear force becomes repulsive.
3. Nuclear forces are charge independent i.e., force between two protons (p-p), the force between two neutrons (n-n) and the force between a neutron and a proton (n-p) are almost equal.
4. The nuclear force is spin-dependent i.e., nucleons with parallel spins have greater nuclear force than the ones with anti-parallel spins.

5. The strength of nuclear forces becomes saturated over a short distance i.e., nucleons interact only with their first neighbours and not beyond that.



Origin of nuclear force:

In 1935, Japanese physicist Yukawa postulated that nuclear forces result from the constant exchange of massive particles called mesons between two nucleons. According to Yukawa, because of short range nature of nuclear forces, a nucleon is surrounded by meson field.When a nucleon is brought near to another nucleon, a meson emitted by one may be absorbed by the other or vice-versa. This way there is a constant transfer of momentum from one nucleon to the other and hence a force is exerted between them.

The emission of a meson ought to reduce the mass of a nucleon. However, this is not observed. Hence, the exchange of meson must take place in a short time that the uncertainty in energy is consistent with Heisenberg's uncertainty principle $\Delta E.\Delta t \sim \hbar$. This makes the experimental detection of meson exchange not possible and hence the mesons in the exchange process are referred to as virtual mesons.

Nucleons interact with each other by exchange of pi mesons which can exist in three different forms. Its neutral form is called neutral pi meson or pion (π°), its negative form is called negative pion (π^{-}) and its positive form is called positive pion (π^{+}).

2. ***Units, dimensions and physical constants***

2.1 The Atomic Mass Unit (a.m.u.)

The mass of a nucleus is given in terms of a unit called the atomic mass unit (a.m.u.) which is equal to one-twelfth the mass of the carbon-12 atom.
Since, the mass of one C^{12} atom in kilogram = $(12 \times 10^{-3})/N_A$

where N_A is Avogadro's number = 6.023×10^{23} mole^{-1}

Therefore, 1 a.m.u. = $(12 \times 10^{-3})/(12 \times 6.023 \times 10^{23}) = 1.66 \times 10^{-27}$ kg.

The atomic mass of an element is the average mass based on the natural isotopic combination. Thus, the atomic mass of carbon is not 12.00000 a.m.u but 12.01115 a.m.u due to the presence of different carbon isotopes in nature.

It is also possible to express the units of mass in terms of energy units based on Einstein's mass energy relationship

$E = mc^2$

Therefore, the energy equivalent to one a.m.u. in terms of joules is

$E = 1 \text{ a.m.u.} \times c^2 = 1.66 \times 10^{-27} \times 9 \times 10^{16} = 1.494 \times 10^{-10}$ J = 931.478 MeV

Therefore, 1 a.m.u = 931.5 MeV.

-Proton mass: 938.280 MeV/c^2 .

-Neutron mass: 938.573 MeV/c^2 .

-Electron mass: 0.511 MeV/c^2 .

3. ***Basic Nuclear Properties***

According to Rutherford model, most of the mass of the atom is concentrated in a small spherical volume called the nucleus, and the electrons are distributed around the nucleus. The radius of the nucleus is about 10^{-13} cm and the spherical volume where electrons are distributed carries radius of about 10^{-8} cm. The protons and neutrons are the only constituents of the nucleus, which are called nucleons.

3.1 Nuclear radius and density: The scattering of α-particles by the nucleus demonstrated that the size of any atom is almost constant, but the size (volume) of any nucleus depends on its mass number A. Assuming a nucleus to be in the form of a sphere, its radius R is given by

$R = r_0 A^{1/3}$

The value of r_0 is found to depend on the type of experiment. In general, it is between 1.2×10^{-13} cm and 1.48×10^{-13} cm.

The density of nucleus is independent of atomic mass number and its value is almost the same for all nuclei.

3.2 Nuclear Angular Momentum or Nuclear Spin

Each nucleon in the nucleus is assumed to have both orbital and spinning motions just like an electron has in an atom. It means each nucleon has both orbital and spin angular momenta. The magnitude of the spin angular momentum is $\hbar/2$ ($\hbar = h/2\pi$). Its orientation in space can be described by only two states: the spin axis is either parallel or antiparallel to any given direction (say z-axis). So the component of spin along z-axis is either $\hbar/2$ or $-\hbar/2$. In view of this, the total angular momentum i of each nucleon is

$i = l \pm s$,

where l is the orbital angular momentum and s is the spin angular momentum. For nuclei having more than one nucleon, l is replaced with L and s is replaced with S, which represent the corresponding total momentum of all the nucleons. Hence, the total angular momentum of the nucleus is given by

$I = L \pm S$

I is actually a vector, whose magnitude is the maximum possible component in any given direction. The value of I is an integral multiple of $\hbar$ for the nuclei with even mass numbers, and it is an odd half-integral multiple of $\hbar$ for the nuclei with odd mass numbers. In particular, even-even nuclei (nuclei with both Z and N even) carry zero value of I. The total nuclear angular momentum I is also termed as nuclear spin.

3.3 Magnetic dipole moment of nucleus

A moving charged particle with intrinsic spin possesses an orbital and spin magnetic dipole moment. Inside a nucleus, a positively charged proton has both orbital and spin magnetic dipole moment while a neutron has only spin magnetic dipole moment. Hence, the resultant magnetic dipole moment μ_I of a nucleus is the vector sum of the magnetic dipole moments of all the nucleons and is given by

$\mu_I = g_I \, \mu_N \, I$

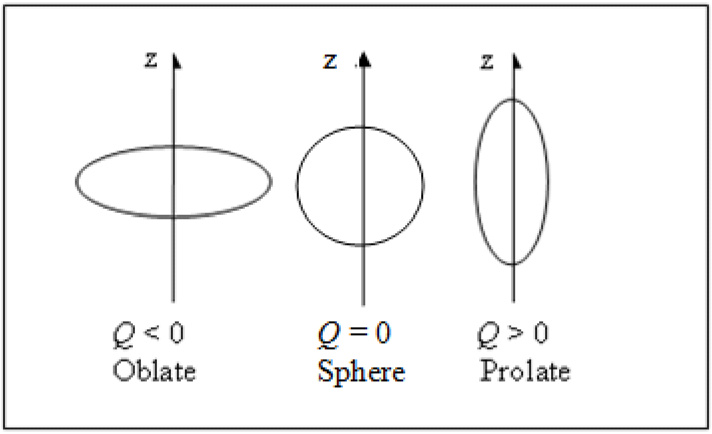
where g_I is the nuclear gyromagnetic ratio and μ_N is the nuclear magneton. The value of nuclear magnetons is 5.05×10^{-27} J/wb/m^2. The measured values of μ_I are between $-3\mu_N$ and $+10\mu_N$. When the magnetic moment of the nucleus is in the opposite direction to the direction of nuclear spin, μ_I carries negative values. The positive valve of μ_I means the directions of the magnetic moment of the nucleus is the same as that of the nuclear spin. The magnetic moment of a proton is $+2.79276\ \mu_I$, whereas that of neutron is $-1.191315\ \mu_I$. This indicates that the proton and neutron have a non-uniform charge distribution, which is also very complex.

3.4 Electric Quadrupole Moment

The electric quadrupole moment is a measure of the deviation of the nucleus from its spherical symmetry. Under the situation of a deviation, the nucleus can be imagined to be an ellipsoid of revolution with its diameter 2b along the axis of symmetry and diameter 2a along the axis perpendicular to this. The quadrupole moment Q of the nucleus, when its electric charge is uniformly distributed throughout the ellipsoid, is given by

$$Q = (2/5)Z(b^2 - a^2)$$

Q is zero for the nuclei having spherical symmetry (a = b) and uniform charge distribution. The magnitude of electric quadrupole moment depends on the magnitude of nuclear charge Z, size of the nucleus (magnitudes of b and a) and the extent of deviation (difference in b and a) from spherical symmetry.



3.5 Binding energies of nuclei

When nuclear masses are measured, it is found that they are less than the sum of the masses of the neutrons and protons of which they are composed. This decrease in mass (ΔM) is converted into energy $\Delta E = \Delta Mc^2$. This energy is called the binding energy (B). The binding energy B of a nucleus is the energy required to break the nucleus into free neutrons and protons.

For a nucleus of mass M containing Z protons and N neutrons, the binding energy B is defined as,

$$B = (ZM_p + NM_n - M)c^2$$

where M_p and M_n represent the masses of free proton and neutron, respectively.

A graph of the binding energy per nucleon (B/A) as a function of the mass number (A) is called binding energy curve. The interesting conclusions that can be drawn from this plot of B/A against A (atomic mass number) is given below:

i. The magnitude of average B/A is approximately 8.8 MeV i.e., B/A does not depend on A. In other words, B/A appears to be approximately independent of the overall size of a nucleus.
ii. B/A falls off at small values of A. This is because very light nuclei have a larger fraction of their nucleons residing on the surface rather than inside. This reduces

the B/A value as a surface nucleon is surrounded by fewer nucleons compared to a nucleon residing in the interior and consequently is not so strongly bound.

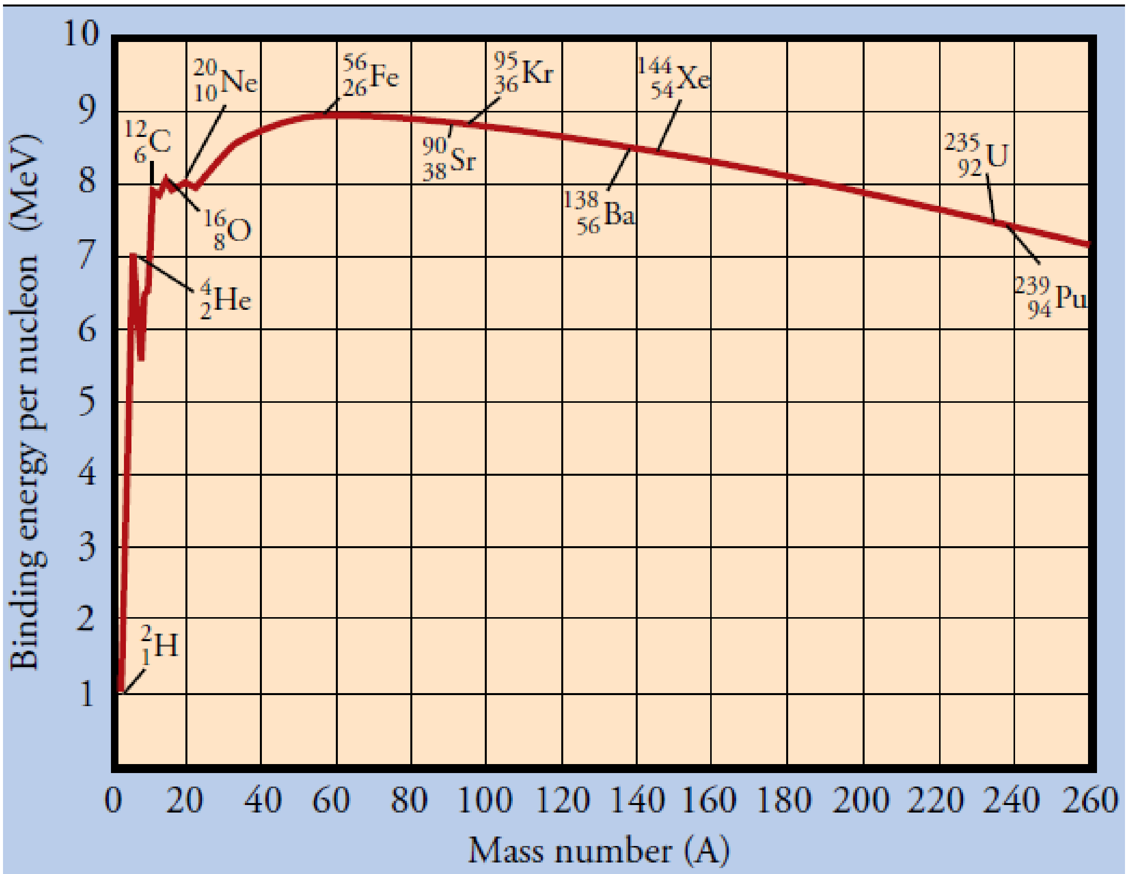
iii. B/A falls off at large values of A. This is due to Coulomb effect. Between every pair of protons, there is a Coulomb repulsion which increases as Z^2. For naturally occurring nuclei, Z^2 increases faster than A and so the Coulomb effect cannot be adequately compensated by an increase in A.

iv. B/A against A plot is peaked around A ~ 60. When the binding energy is increased, energy in other forms can be released, since a decrease in M corresponds to conversion of mass into energy. These considerations highlight the importance of fission and fusion reactions, which are basic in the production of nuclear energy.

v. The peak of this plot corresponds to Fe. This explains for the large abundance of Fe in nature.

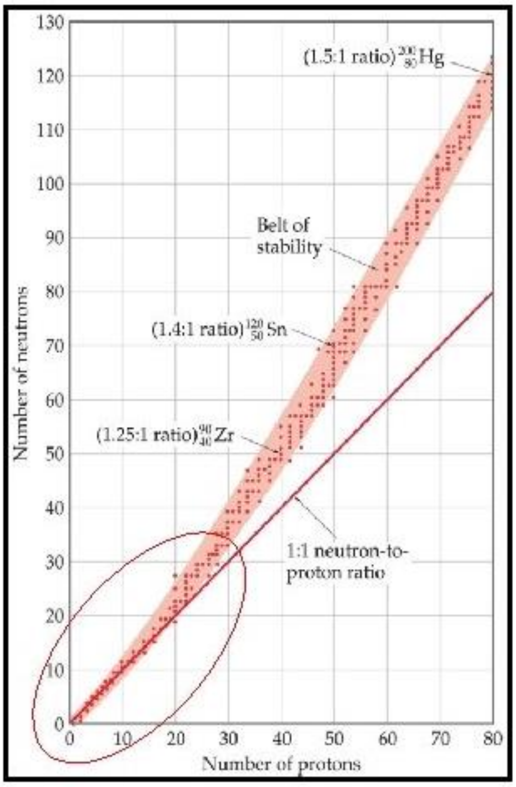
vi. The magnitude of binding is strong for mass numbers 4, 8, 12, 16, 20 and 24 i.e., mass numbers which are multiples of four particles (2 neutrons + 2 protons). This effect is due to a pairing force which exists between pairs of neutrons and pairs of protons.

vii. The value of B/A against A plot shows discontinuities at neutron or proton number values 2, 4, 8, 20, 50, 82 and 126. These numbers are termed as nuclear magic numbers. At these values of neutron or proton numbers, the binding energy is found to be unusually large. Large binding energy means high stability. This high stability is reflected in high abundance of isotopes with these proton numbers and isotones with these neutron numbers.



Nuclear Stability

Certain isotopes are more stable than others. Their stability is determined by the ratio of the number of neutrons to the number of protons in the nucleus termed as the Segre plot. At low atomic masses, the stable ratio is approximately 1:1. At about an atomic mass number of 20 this starts to increase until it is around 1.5:1 for the very heavy elements. This is due to the fact that with higher numbers of protons more neutrons are needed due to the repulsion of the protons from electrostatics. This ratio is not exact but represents a "band of stability" around which unstable isotopes cluster. There are a large number of unstable isotopes both above the band (too high a number of neutrons) and below the band (too high a number of protons). At some point there are no longer any stable isotopes regardless of the neutron to proton ratio. This can be seen at very high atomic numbers. Above mass 208 there are no stable isotopes.



The isotopes on both sides of the stability curve are radioactive, which decay in such a way that the final product lies on the stability curve and is now stable.

The total binding energy of a nucleus depends not only on the ratio N/Z but also on whether these numbers of neutrons and protons are odd or even. This is called odd-even effect. All the stable nuclei can be classified into four groups, namely even-even, even-odd, odd-even and odd-odd, based on number of protons and neutrons, respectively. Even-even nuclei having even number of mass number A are the most abundant, i.e., these nuclei are most stable, whereas odd-odd nuclei are very few. The stability of odd-even and even-odd lies between the two extremes.

Data collected for stable nuclei suggests that nucleons tend to form neutron-proton pairs. This is called pairing of nucleons, according to which nuclei that satisfy the condition A/2 = Z or A

= 2Z are more strongly bound together and any deviation from A = 2Z should decrease the binding energy.

3.7 Nuclear Models

In the absence of a detailed theory of nuclear structure, attempts were made to correlate the nature of variation of binding energy per nucleon in terms of various models. Several models were proposed. Each of them were based on a set of simplifying assumptions and hence, was useful in a limited way only. The nuclear models include the shell or independent particle model, liquid drop model, collective nuclear model and the optical model for nuclear reactions. The shell model and the liquid drop models are the most important and useful models of nuclear structure.

B. Nuclear Reactions and their types

Definition of nuclear reaction: A nuclear reaction is considered to be the process in which two atomic nuclei or subatomic particles interact to produce one or more new particles or gamma rays.

1. *Nuclear Reactions: Conservation Laws*

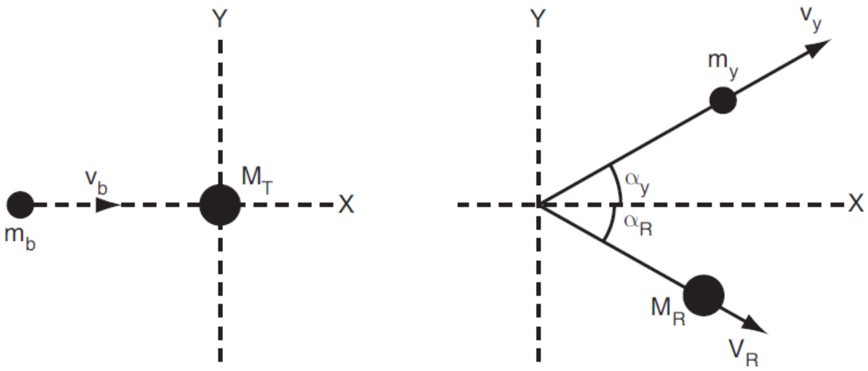
If a target material is bombarded by fast-moving particles such as protons, neutrons, electrons, deuterons or alpha particles, then the target nuclei after the bombardment are usually different from what they were before. The target nuclei may change their mass number or atomic number or both due to interaction with an incident particle. This is called a transmutation and the reaction is called nuclear reaction.

The collision of a bombarding particle of rest mass m_b and kinetic energy U_b with a target containing nuclei of rest mass M_T and kinetic energy U_T results in the nuclear reaction.

$$U_b + N_T \rightarrow N_R + y$$

In this interaction a recoil nucleus N_R of rest mass M_R with kinetic energy U_R and a light particle y of rest mass m_y with kinetic energy U_y are emitted. As per the law of conservation of energy, total initial energy T_i that is the sum of the rest mass energies and kinetic energies must be equal to the total final energy, T_f .

$$T_i = T_f$$
$$m_b c^2 + U_b + M_T c^2 + U_T = M_R c^2 + U_R + m_y c^2 + U_y$$
$$[(U_R + U_y) - (U_T - U_b)] = [(M_T + m_b)c^2 - (M_R + m_y)c^2]$$
$$U_f - U_i = M_i c^2 - M_f c^2$$



Before collision After collision

where $U_i = U_T + U_b$ and $U_f = U_R + U_y$ together with U_i and U_f as the initial and final kinetic energies and M_i and M_f as the total initial and final rest masses, given by $M_i = M_T + m_b$ and $M_f = M_R + m_y$. The above equation states that the net increase in kinetic energy is equal to the net decrease in rest mass energy that is equal to the disintegration energy or Q-value. Hence Q-value is defined as

$$Q = U_f - U_i = M_i c^2 - M_f c^2$$

1.1 Exoergic and Endoergic Reactions

If the Q-value is positive, then the nuclear reaction is called exoergic reaction and in this case $U_f > U_i$ or $M_i c^2 > M_f c^2$. If Q-value is a negative quantity, then the nuclear reaction is an endoergic reaction and in this case $U_f < U_i$ or $M_i c^2 < M_f c^2$. If initially the target nucleus is at rest, then its kinetic energy $U_T = 0$. Hence, Q-value of a reaction is given by

$$Q = (U_R + U_y) - U_b$$
$$= [(M_T + m_b) - (M_R + m_y)]c^2$$

An exoergic reaction is energetically possible if the bombarding particle has zero kinetic energy i.e., $U_b = 0$.

On the other hand, endoergic reaction is energetically possible only when

$U_b > |Q|$. The minimum kinetic energy of the bombarding particle necessary to initiate the endoergic reaction is called threshold energy $(U_b)_{min}$.

$$(U_b)_{\min} = \left(\frac{M_T + m_b}{M_T}\right)|Q| = \left(1 + \frac{m_b}{M_T}\right)|Q|$$

2. *Nuclear fission*

The phenomenon of breaking of a heavy nucleus into two or more light nuclei of almost equal masses together with the release of a huge amount of energy is known as nuclear fission. The process of nuclear fission was first discovered by the German scientists, Otto Hahn and Strassman, in the year 1939. In this process, when uranium nucleus ($^{235}_{92}U$) was bombarded with slow neutrons, this nucleus was found to split up into two radioactive nuclei which were identified as isotopes of barium ($^{144}_{56}Ba$) and krypton ($^{89}_{36}Kr$). It is given by the following nuclear reaction.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow \left[{}^{236}_{92}\mathrm{U}\right] \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3{}^{1}_{0}n + \text{energy}$$

It is not that barium and krypton are the only isotopes to be obtained by the fission of ($^{235}_{92}U$). Actually, this is a very complicated phenomenon and more than 100 isotopes of over 20 different elements have been obtained in it. All these elements fall in the middle 75 to 160 mass number region of the periodic table.

3.1 Nuclear Energy

In nuclear fission, a huge amount of energy is liberated, which is known as nuclear energy. An estimation of this energy can be made as follows. The mass of

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n = 234.99 \text{ amu} + 1.01 \text{ amu} = 236.0 \text{ amu}$$

Similarly, the mass of

$$\begin{aligned} ^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}n &= 143.87 \text{ amu} + 88.90 \text{ amu} + 3 \times 1.01 \text{ amu} \\ &= 235.80 \text{ amu} \end{aligned}$$

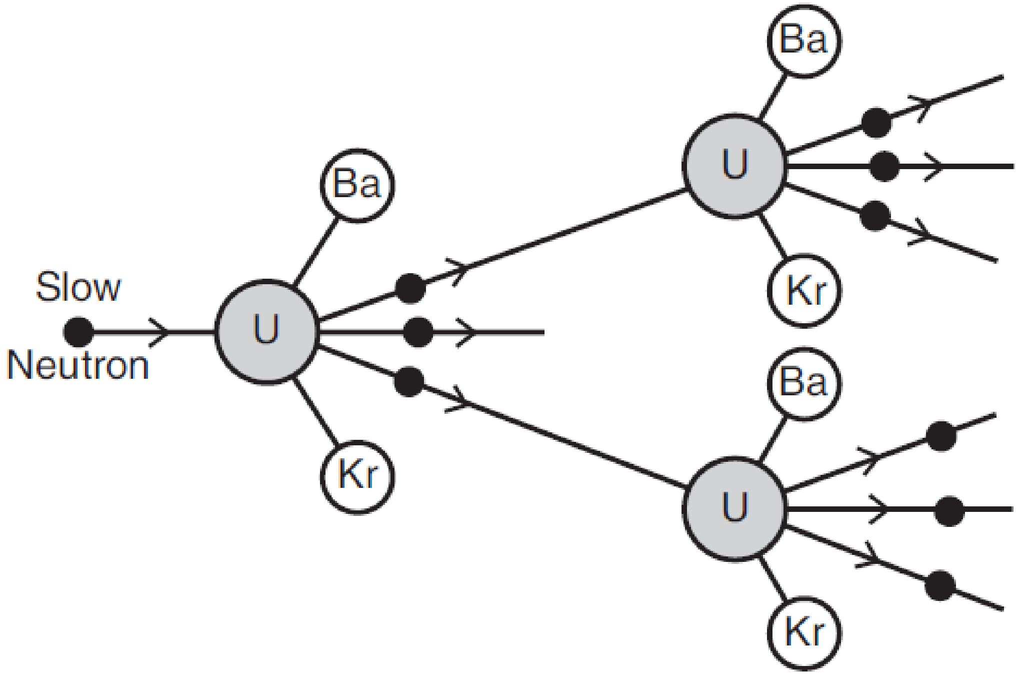
$$\text{Mass defect } \Delta m = 236.00 - 235.80 = 0.20 \text{ amu}$$

According to Einstein's mass-energy relation, $E = mc^2$, 1 amu mass is equivalent to 931 MeV energy. So, energy released in each fission process = 0.20 X 931 ≈ 190 MeV. This energy is millions of times more than what we get by any chemical reaction.

3.2 Chain Reaction

When uranium is bombarded by neutrons, each uranium nucleus is broken into two nearly equal fragments and a huge amount of energy is liberated and two or three fresh neutrons are emitted. If the conditions are favourable, these neutrons take part in the fission of other uranium nuclei in the same way. This leads to a chain of nuclear fissions which continues till the whole of uranium is fissioned within a fraction of time. Thus the energy produced in nuclear fission goes on multiplying. This energy takes a tremendous magnitude very soon and is released as a violent explosion. Such a chain reaction is known as uncontrolled chain reaction. This happens in an atom bomb.

If by some means, the reaction is controlled in such a way that only one of the neutrons produced in each fission is able to cause further fission, then the fission process is slow and the energy is released steadily. This chain reaction is known as controlled chain reaction. This happens in nuclear reactors.



3.3 Critical size of nucleus

Consider a spherically shaped uranium nucleus of radius r, which has N_1 number of neutrons produced in a given time interval, N_2 number of neutrons lost in non-fission process and N_3 number of neutrons escaping through the surface in the same time interval. N_1 and N_2 will be proportional to the volume, whereas N_3 will be proportional to the surface area of the sphere,

$$N_1 \propto \frac{4}{3}\pi r^3 = k_1 r^3$$

$$N_2 \propto \frac{4}{3}\pi r^3 = k_2 r^3$$

$$N_3 \propto 4\pi r^2 = k_3 r^2$$

where k_1, k_2 and k_3 are proportionality constants. The chain reaction is possible only when the rate of emission of neutrons is greater than the total number of neutrons absorbed within the substance and going out of the substance.

$$N_1 > N_2 + N_3$$

$$k_1 r^3 > k_2 r^3 + k_3 r^2$$

$$(k_1 - k_2) r > k_3$$

$$r > \frac{k_3}{k_1 - k_2} = k$$

where k is known as the critical size of the nucleus. Thus, in order to achieve a self sustained chain reaction, the size of the sample must be greater than a critical value k. Below this critical value the chain reaction will stop.

C. Nuclear Radiation Counters

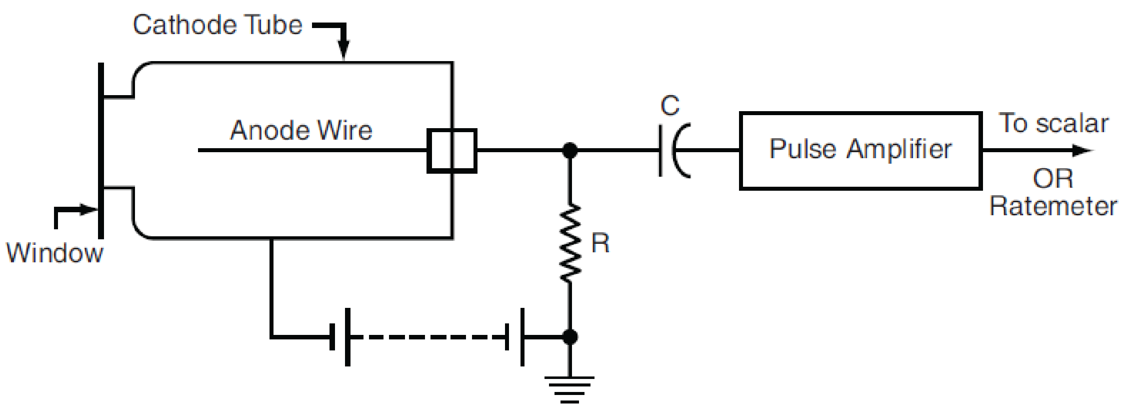
The detection of nuclear radiations depends upon their interaction with matter and especially on the excitation and ionisation processes. Nuclear–radiation detector is a device in which the presence of radiation induces physical change that is observable. The principles of nuclear radiation detection can be broadly sub-divided into three classes:

a. Methods based on detection of free charge carriers: These are applicable for the detection of charged as well as uncharged particles. Instruments based on this method include ionization chambers, proportional counters and GM counters.

b. Methods based on the visualization of the tracks of the radiation: These are applicable for the detection of charged particles and include instruments like the Wilson cloud chamber, bubble chamber and nuclear emulsions.
c. Methods based on light sensing: These are also applicable for detection of both charged and uncharged particles. Instruments based on this method include scintillation counters and Cerenkov detectors.

Geiger-Mueller Counter

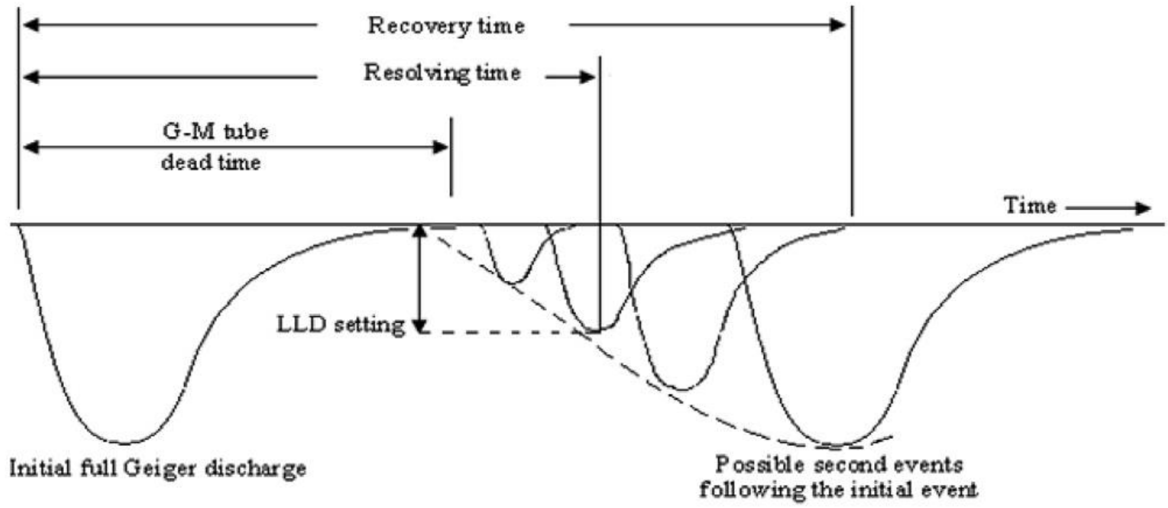
Geiger–Mueller or GM counter is most efficient, accurate and useful device, which is used for detecting individual particles such as α-, β-, γ- and X-rays. It consists of a metallic cylindrical tube fitted with an axial fine tungsten wire. One end window of this tube is sealed by thin mica sheet through which radiation can enter the tube. The whole arrangement is enclosed within a thin glass chamber. This tube is filled with a gaseous mixture of about 90% argon and 10% ethyl alcohol at a pressure of 10 cm of Hg. The potential of the order of 1000 volts is applied between anode and cathode. The value of this applied voltage is adjusted to be somewhat below the breakdown potential of the gaseous mixture. When radiation enters the GM tube, some of the argon atoms get ionised and produce number of ion-pairs and then electrons are moved to the anode. Due to the shape of electrodes, the electrostatic field is radial and it acts strongly near the anode. When electrons move towards the anode, they collide with gas molecules and produce further ionisation. In this process, the multiplication of ions continues and as a result, avalanche of electrons is obtained. If the exciting potential is sufficiently high, the secondary ionisation takes place and further another avalanche of electrons is obtained. Thus, within no time almost entire volume of the gas in the tube is ionised and it leads to an amplification as high as 10^8. In ionisation process, the total number of ions produced does not depend upon radiation entered.



Dead time, resolving time and recovery time of a G-M counter:

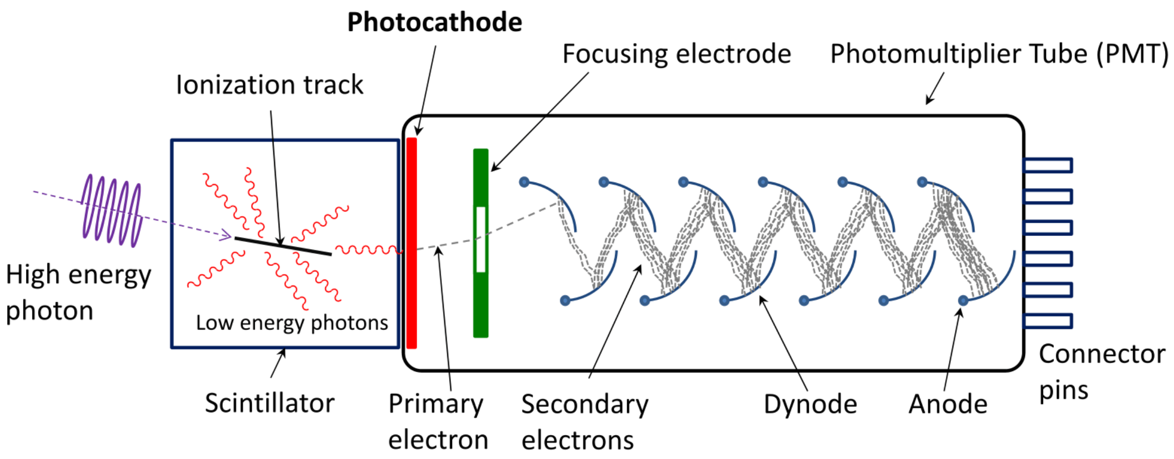
In a GM counter, electrons are collected at the anode rather quickly, positive ions tend to wander longer around the anode due to their low mobility before being collected at the cathode. Presence of positive charge results in severe distortion of the electric field. Any subsequent event during the time when the electric field is distorted will either produce no pulse at all or produce a pulse with reduced amplitude, which may or may not be detected by the subsequent counting system. Therefore G-M counters are prone to dead-time count losses. There is a minimum electric field necessary to collect the negative charge and produce any pulse in the tube. Dead-time is the time required for the electric field to recover to a level such that a second pulse of any size can be produced. Just after the dead-time, the electric field gradually recovers during this time the amplitude of the second pulse is hampered by the presence of the lingering positive charge. Therefore immediately after the dead-time, if a second pulse is produced its amplitude will be reduced.

There is minimum amplitude needed for the second pulse for it to pass through the discrimination threshold and be recorded. The time needed between the two pulses to produce this minimum amplitude recordable second pulse is called the resolving time of the detection system. Since the true dead-time is impossible to measure, resolving time is often referred to as deadtime of the G-M counter. Finally, after complete recombination of the gas in the Geiger tube a full amplitude pulse can be produced. The minimum time required to produce a full amplitude pulse is called as the recovery time of the detection system. Typically, the dead-time for a GM detector is of the order of hundreds of microseconds.



Scintillation detectors

A scintillation counter is an instrument for detecting and measuring ionizing radiation viz, γ-, β- and γ-rays by using the excitation effect of incident radiation on a scintillator material and detecting the resultant light pulses.



It consists of a scintillator that generates photons in response to incident radiation, a sensitive photomultiplier tube (PMT) which converts the light to an electrical signal and electronics to process this signal.

Operation

When an ionizing particle passes into the scintillator material, atoms are ionized along a track. For charged particles the track is the path of the particle itself. For gamma rays (uncharged), their energy is converted to an energetic electron via either the photoelectric effect, Compton scattering or pair production. The chemistry of atomic de-excitation in the scintillator produces a multitude of low-energy photons, typically near the blue end of the visible spectrum. The number of such photons is in proportion to the amount of energy deposited by the ionizing particle. Some portion of these low-energy photons arrive at the photocathode of an attached photo multiplier tube. The photocathode emits at most one electron for each arriving photon by the photoelectric effect. This group of primary electrons is electrostatically accelerated and focused by an electrical potential so that they strike the first dynode of the tube. The impact of a single electron on the dynode releases a number of secondary electrons, which are in turn accelerated to strike the second dynode. Each subsequent dynode impact releases further electrons, and so there is a current amplifying, effect at each dynode stage. Each stage is at a higher potential than the previous to provide the accelerating field. The resultant output signal at the anode is in the form of a measurable pulse for each group of photons that arrived at the photocathode and is passed to the processing electronics. The pulse carries information about the energy of the original incident radiation on the scintillator. The number of such pulses per unit time gives information about the intensity of the radiation. In some applications individual pulses are not counted, but rather only the average current at the anode is used as a measure of radiation intensity. The scintillator must be shielded from all ambient light so that external photons do not swamp the ionization events caused by incident radiation. To achieve this a thin opaque foil, such as aluminized mylar, is often used, though it must have a low enough mass to minimize undue attenuation of the incident radiation being measured.

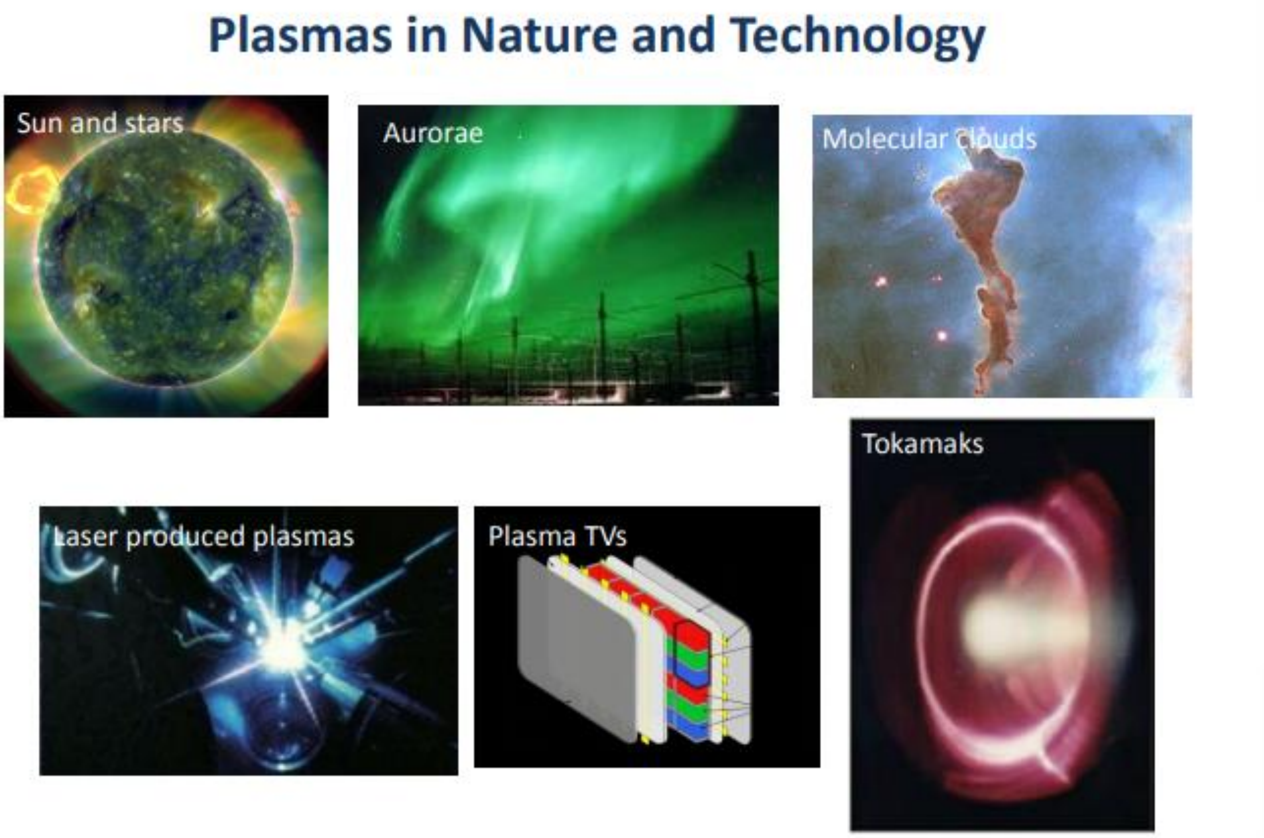
This counter has many advantages over a GM counter. The efficiency of this counter for counting γ-rays is comparatively much higher. The time of flight of the electrons through this tube is so small that it can count about 10^6 particles per second.

PART II – PLASMA PHYSICS Basic concepts of Plasma physics:

Plasma as a state of matter, Debye length, plasma frequency, Applications of plasma physics.

Plasma as a state of matter

In the ancient phlogiston theory there was a classification of the states of matter: i. e., "earth", "water", "air", and "fire". While the phlogiston theory had certain basic defects, it did properly enumerate the four states of matter – solid, liquid, gas, and plasma. It is estimated that more than 99% of the matter in the universe exists in a plasma state.



As the temperature of any solid material is raised, its state changes from solid to liquid and then to gas. If we increase the temperature of a gas beyond a certain limit, it enters a regime where the thermal energy of its constituent particle is so great that the electrostatic forces, which ordinarily bind electrons to atomic nuclei, are overcome. Instead of hot gas composed of electrically neutral atoms, we then have a mixed population of charged and neutral particles. With increasing temperature, the number of ionized particles increases and the ionized gas starts behaving differently. After the fraction of ionized particles is sufficiently high the ionized gas starts exhibiting the collective behavior and the state of matter is plasma, and it is neither solid nor liquid nor gas. Plasma is thus defined as a quasi-neutral gas of charge and neutral particles, which exhibits collective behavior. Here are some familiar examples of plasmas:

1. Lightning, Aurora Borealis, and electrical sparks. All these examples show that when an electric current is passed through plasma, the plasma emits light (electromagnetic radiation).

2. Neon and fluorescent lights, etc. Electric discharge in plasma provides a rather efficient means of converting electrical energy into light.

3. Flame. The burning gas is weakly ionized. The characteristic yellow color of a wood flame is produced by 579 nm transitions (D lines) of sodium ions.

4. Nebulae, interstellar gases, the solar wind, the earth's ionosphere, the Van Allen belts. These provide examples of a diffuse, low temperature, ionized gas.

5. The sun and the stars. Controlled thermonuclear fusion in a hot, dense plasma provides us with energy (and entropy!) on earth.

Plasma Production

A plasma can be produced by raising the temperature of a substance until a reasonably high fractional ionization is obtained. Under thermodynamic equilibrium conditions, the degree of ionization and the electron temperature are closely related. Although plasmas in local thermodynamic equilibrium are found in many places in nature, as is the case for many astrophysical plasmas, they are not very common in the laboratory. Plasmas can also be generated by ionization processes that raise the degree of ionization much above its thermal equilibrium value. There are many different methods of creating plasmas in the laboratory and, depending on the method, the plasma may have a high or low density, high or low temperature, it may be steady or transient, stable or unstable, and so on. In what follows, a brief description is presented of the most commonly known processes of photoionization and electric discharge in gases.

In the photoionization process, ionization occurs by absorption of incident photons whose energy is equal to, or greater than, the ionization potential of the absorbing atom. The excess energy of the photon is transformed into kinetic energy of the electron-ion pair formed. For example, the ionization potential energy for the outermost electron of atomic oxygen is 13.6 eV, which can be supplied by radiation of wavelength smaller than about 91 nm, i.e., in the far ultraviolet. Ionization can also be produced by x-rays or gamma rays, which have much smaller wavelengths. The Earth's ionosphere, for example, is a natural photoionized plasma.

In a gas discharge, an electric field is applied across the ionized gas, which accelerates the free electrons to energies sufficiently high to ionize other atoms by collisions. One characteristic of this process is that the applied electric field transfers energy much more efficiently to the light electrons than to the relatively heavy ions. The electron temperature in gas discharges is therefore usually higher than the ion temperature, since the transfer of thermal energy from the electrons to the heavier particles is very slow. When the ionizing source is turned off, the ionization decreases gradually because of recombination until it reaches an equilibrium value consistent with the temperature of the medium. In the laboratory the recombination usually occurs so fast that the plasma completely disappears in a small fraction of a second.

Debye length

The properties of a plasma are markedly dependent upon the particle interactions and external potentials. One of the basic features that distinguish the behavior of plasmas from that of ordinary fluids and solids is the existence of collective effects. Due to the long range of electromagnetic forces, each charged particle in the plasma interacts simultaneously with a considerable number of other charged particles, resulting in important collective effects that are responsible for the wealth of physical phenomena that take place in a plasma. The particle dynamics in a plasma is governed by the internal fields due to the nature and motion of the particles themselves, and by externally applied fields. The basic particle interactions are electromagnetic in character. Quantum effects are negligible, except for some cases of close collisions. In a plasma, we must distinguish between charge-charge and charge neutral interactions. A charged particle is surrounded by an electric field (external potential) and interacts with the other charged particles according to the Coulomb force law, with its dependence on the inverse of the square of the separation distance.

Plasma possesses a special ability to shield out external potentials that are applied to it within a very small region. The external potential $\phi_\circ$ applied to a plasma is distributed into the plasma as;

$$\phi(x) = \phi_\circ \, e^{\frac{|x|}{\lambda_D}} \qquad (1)$$

Where, λ_D is the Debye length expressed as

$$\lambda_D = \left(\frac{\varepsilon_o \, KT_e}{ne^2}\right)^{\frac{1}{2}} \qquad (2)$$

ε_o is the permittivity of free space, T_e is the electron temperature, e is the electronic charge and K is the Boltzmann constant.

The Debye length is an important physical property for the description of plasma. It provides a measure of the distance over which the influence of external potential is felt by the other charged particles inside the plasma. It is obvious that the charged particles arrange themselves in such a way that the external electrostatic fields are shielded within a distance of the order of a few Debye lengths. This property is called the Debye shielding and for plasma to exhibit the collective behavior the Debye length must be much smaller than its characteristic length so that the majority of plasma particle are not influenced by the external potential. Consequently, charge in the plasma interacts collectively only with the charges those lie inside its Debye sphere, its effect on the other charges being effectively negligible charge in the plasma interacts collectively only with the charges those lie inside its Debye sphere, its effect on the other charges being effectively negligible.

Plasma Frequency

If the electrons in a quasi-neutral plasma are displaced from its equilibrium position an electric field will be built in such a direction such that it will try to restore the neutrality of the plasma by pulling the electrons back to their original positions. As the ions are massive compared to the electrons they form a uniform background. Due to inertia, the electrons will overshoot and oscillate about their equilibrium positions with a characteristic frequency, which is known as plasma frequency. This oscillation is so fast that the massive ions do not have time to respond to the oscillating electric field and may be considered as fixed.

The plasma frequency is given by

$$\omega_p = \left(\frac{n_0 e^2}{m_e \epsilon_0}\right)^{\frac{1}{2}}$$

Where m_e stand for the mass of an electron. For the properties of the plasma to be determined by electromagnetic rather than hydrodynamic collision, the plasma frequency must be a large compound to the ordinary collision frequency. Table-1 has few examples of plasma frequencies;

Noble Metal	Electron Density (10^{22}/cm^3)	Plasma Frequency (10^{16} Hz)
Gold (Au)	5.87	1.41
Silver (Ag)	5.66	1.32
Copper (Cu)	8.47	1.65

Table-1: Electron density and plasma frequency values of Au, Ag and Cu noble nanoparticles.

Applications

Plasma processing of materials is now becoming a critical technology not only in the electronics industry but also in the aerospace, automotive, steel, biomedical, textile, optics and paper industries. Due to the diversity of applications, plasma processing will in the near future, have to cover a broad range of geometries, dimensions, chemical systems, electromagnetic designs and plasma-surface interactions. In addition, at the industrial level, plasma processing of materials usually imposes the uniformity of the surface treatment. In this situation, the technological challenge consists in developing surface processes able to meet the required specifications, especially in terms of uniformity and processing rate, and furthermore, the possibility of transferring processes from one reactor to another, or more generally, scaling processes from a small to a large reactor.

Etching (Sputtering)

When an energetic ion strikes a solid surface, one or more atoms can be ejected from the solid. This process is called sputtering (or sometimes ion milling) and is used to etch solids. In sputter etching, the sub- state to be etched (the target) is placed on one electrode of the system. A glow discharge is generated in a low-pressure gas. The ions, accelerated through the sheath, strike and sputter the target. The discharge can be excited by a DC, RF or microwave electric field in many different configurations. Magnetic fields can be used to enhance plasma density. Typically, an inert gas such as argon is used. But reactive gasses can also be used (reactive sputter etching). Plasma etching. Though sputtering is technically "plasma etching," the term usually refers to processes where chemical reactions are at work. Many plasma etching systems (called etching tools) operate over a wide range of gas pressures. Plasmas are generated with RF or microwave voltages ranging in frequency from kHz to GHz.

Deposition/coating

Sputter coating. Sputtering can be used as a deposition process as well as an etching process. Sputter coating removes material from a target, which is then redeposited on a substrate. This is a common method of thin film deposition for metals such as molybdenum or tungsten. While inert gases are typically used, reactive sputter coating utilizes reactive gases to deposit modified coatings. For example, silicon nitride (Si_3N_4) films can be deposited using a Si target and an N2 plasma.

Plasma Surface Cleaning

Glow discharge cleaning is similar to sputtering, except that impurities on the surface of the material are removed. This process is used to clean such things as vacuum surfaces and medical instruments.

High Voltage Engineering

Vacuum tubes have largely been replaced by solid-state technology. However, they still dominate in high power microwave systems. Modern microwave tubes have attained peak powers > 100 MW, average powers z 1 MW, and operating frequencies up to hundreds of GHz. These are performance levels solid-state devices may never attain. Microwave tubes have widespread applications in radar, communications and microwave cooking. For example, microwave ovens are powered by magnetron tubes, and communications satellites contain amplifier tubes, most often Travelling Wave Tubes (TWTs).

Environmental engineering

High energy plasma particles can be used to catalyze chemical reactions. This can be useful in processing pollutants and hazardous waste. Plasma waste processing has been applied to industrial pollutants such as sulfur dioxide (S02) and nitrogen- oxygen compounds (NO,), solvents such as acetone and trichloroethylene and volatile organic compounds such as toluene and automobile emissions. Plasmas have also been used to process low-level radioactive waste via verification. This is where the material is reduced in volume and transformed into a glassy obsidian. The vitrified substance has much lower leachability than unprocessed material. Other hazardous wastes with potential for plasma treatment are PCBs, dioxins, nerve gas and pesticides

Laser induced plasma

Plasma ignition processes include bond breaking during ionization and excitation; these bond breaking mechanisms can generate a laser pulse in the form of energy.

Laser induced plasma has been used for different diagnostic and technological applications as detection, thin film deposition, and elemental identification. The possible interferences of atomic or molecular species are used to specify organic, inorganic or biological materials which allows critical applications in defense (landmines, explosive, forensic (trace of explosive or organic materials), public health (toxic substances pharmaceutical products), or environment (organic wastes). Laser induced plasma for organic material potentially provides fast sensor systems for explosive trace and pathogen biological agent detection and analysis.