DEPARTMENT OF PHYSICS
GOVT. DEGREE COLLEGE, KULGAM

5^{TH} SEMESTER NUCLEAR PHYSICS (Unit IV)

ORIGIN OF NUCLEAR PHYSICS

Nuclear physics as a subject distinct from atomic physics could be said to date from 1896, the year that Becquerel observed that photographic plates were being fogged by an unknown radiation emanating from uranium ores. He had accidentally discovered *radioactivity*: the fact that some nuclei are unstable and spontaneously decay. The name was coined by Marie Curie two years later to distinguish this phenomenon from induced forms of radiation. In the years that followed, radioactivity was extensively investigated, notably by the husband and wife team of Pierre and Marie Curie, and by Rutherford and his collaborators, and it was established that there were two distinct types of radiation involved, named by Rutherford α and β rays. We know now that α rays are bound states of two protons and two neutrons (we will see later that they are the nuclei of helium atoms) and β rays are electrons. In 1900 a third type of decay was discovered by Villard that involved the emission of photons, the quanta of electromagnetic radiation, referred to in this context as γ rays. These historical names are still commonly used.

At about the same time as Becquerel's discovery, J.J. Thomson was extending the work of Perrin and others on the radiation that had been observed to occur when an electric field was established between electrodes in an evacuated glass tube and in 1897 he was the first to definitively establish the nature of these 'cathode rays'. We now know the emanation consists of free *electrons*, (the name 'electron' had been coined in 1894 by Stoney) denoted e^- (the superscript denotes the electric charge) and Thomson measured their mass and charge. The view of the atom at that time was that it consisted of two components, with positive and negative electric charges, the latter now being the electrons. Thomson suggested a model where the electrons were embedded and free to move in a region of positive charge filling the entire volume of the atom – the so-called 'plum pudding model'.

This model could account for the stability of atoms, but could not account for the discrete wavelengths observed in the spectra of light emitted from excited atoms. Neither could it explain the results of a classic series of experiments started in 1911 by Rutherford and continued by his collaborators, Geiger and Marsden. These consisted of scattering α particle by very thin gold foils. In the Thomson model, most of α particles would pass through the foil, with only a few suffering deflections through small angles. Rutherford suggested they look for large-angle scattering and indeed they found that some particles were scattered through very large angles, even greater than 90 degrees. Rutherford showed that this behaviour was not due to multiple small-angle deflections, but could only be the result of the α particles encountering a very small positively charged central *nucleus.*

To explain the results of these experiments Rutherford formulated a 'planetary' model, where the atom was likened to a planetary system, with the electrons (the 'planets') occupying discrete orbits about a central positively charged nucleus (the 'Sun'). Because photons of a definite energy would be emitted when electrons moved from one orbit to another, this model could explain the discrete nature of the observed electromagnetic spectra when excited atoms decayed. In the simplest case of hydrogen, the nucleus is a single *proton* (p) with electric charge $+e$, where e is the magnitude of the charge on the electron, orbited by a single electron. Heavier atoms were considered to have nuclei consisting of several protons. This view persisted for a long time and was supported by the fact that the masses of many naturally occurring elements are integer multiples of a unit that is about 1 % smaller than the mass of the hydrogen atom. Examples are carbon and nitrogen, with masses of 12.0 and 14.0 in these units. But it could not explain why not all atoms obeyed this rule. For example, chlorine has a mass of 35.5 in these units. However, about the same time, the concept of *isotopism* (a name coined by Soddy) was conceived. *Isotopes* are atoms whose nuclei have different masses, but the same charge. Naturally occurring elements were postulated to consist of a mixture of different isotopes, giving rise to the observed masses.

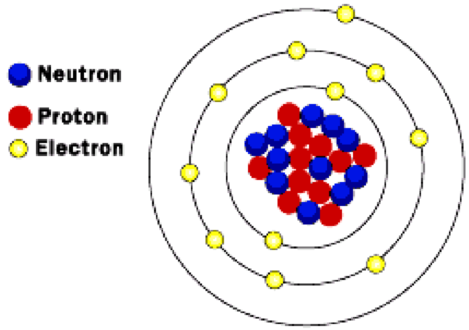
The explanation of isotopes had to wait twenty years until a classic discovery by Chadwick in 1932. His work followed earlier experiments by Irene Curie (the daughter of Pierre and Marie Curie) and her husband Frederic Joliot. They had observed that neutral radiation was emitted when α particles bombarded beryllium and later work had studied the energy of protons emitted when paraffin was exposed to this neutral radiation. Chadwick refined and extended these experiments and demonstrated that they implied the existence of an electrically neutral particle of approximately the same mass as the proton. He had discovered the neutron (n) and in so doing had produced almost the final ingredient for understanding nuclei.

There remained the problem of reconciling the planetary model with the observation of stable atoms. In classical physics, the electrons in the planetary model would be constantly accelerating and would therefore lose energy by radiation, leading to the collapse of the atom. This problem was solved by Bohr in 1913. He applied the newly emerging quantum theory and the result was the now well-known Bohr model of the atom. Refined modern versions of this model, including relativistic effects described by the Dirac equation (the relativistic analogue of the Schrodinger equation that applies to electrons), are capable of explaining the phenomena of atomic physics. Later workers, including Heisenberg, another of the founders of quantum theory, applied quantum mechanics to the nucleus, now viewed as a collection of neutrons and protons, collectively called nucleons. In this case however, the force binding the nucleus is not the electromagnetic force that holds electrons in their orbits, but is a short-range force whose magnitude is independent of the type of nucleon, proton or neutron (i.e. charge-independent). This binding interaction is called the strong nuclear force.

These ideas still form the essential framework of our understanding of the nucleus today, where nuclei are bound states of nucleons held together by a strong charge-independent short-range force. Nevertheless, there is still no single theory that is capable of explaining all the data of nuclear physics and we shall see that different models are used to interpret different classes of phenomena.

NUCLEAR COMPOSITION:

The Nucleus of an atom consists of a tightly packed arrangement of protons and neutrons. These are the two heavy particles in an atom and hence 99.9% of the mass is concentrated in the nucleus. Of the two, the protons possess a net positive charge and hence the nucleus of an atom is positively charged on the whole and the negatively charged electrons revolve around the central nucleus. Since the mass concentration at the nucleus of an atom is immense the nuclear forces holding the protons and the neutrons together are also large. The protons are in such close vicinity to each other inside the tiny nucleus and therefore the electrostatic forces of repulsion also act inside the nucleus. Nuclear energy relies on nothing but releasing the energy trapped in the nucleus of an atom. The total number of protons in a nucleus is equal to the number of electrons revolving around the nucleus and hence the atom, on the whole, is electrically neutral.



It is quite logical to assume that nuclei contain electrons. For example, a good guess might be that half of an atom's electrons are contained within the nucleus, and reduce the electrostatic repulsive forces between protons. Besides the Coulomb repulsion mentioned above facts which suggest the nucleus might contain electrons are nuclide masses, which are nearly multiples of the hydrogen mass (which contains an electron). In addition, some nuclei undergo beta decay, in which an electron is spontaneously emitted from the nucleus. But other experiments demonstrate that the nucleus cannot contain electrons. Here are some reasons why.

Reason 1 -nuclear size. The Heisenberg uncertainty principle places a lower bound on the energies of particles confined to a nucleus. Take a typical nucleus of radius $5x10^{-15}$ m. Suppose an electron exists inside the nucleus. The estimated momentum corresponds to a kinetic energy of at least 20 MeV. Experimentally, electrons emitted during nuclear decay are found to have only 2 or 3 MeV of energy. This isn't nearly enough to correspond to an electron escaping from a nucleus. On the other hand, protons, with their much larger masses, would only need to have a few tenths of an MeV of energy to be confined to a nucleus. This is within the realm of possibility.

Reason 2 - nuclear spin. Electrons and protons both have spins of 1/2. A deuteron (an isotope of hydrogen) is known to have a mass roughly equal to two protons. If the deuteron nucleus contains two protons and one electron (whose mass is small enough to not worry about here), then the deuterium should have a nuclear spin of ±½ or ±3/2 (±½ ±½ ±½). The deuterium nuclear spin is measured to be 1. Its nucleus cannot contain an electron.

Reason 3 - nuclear magnetic moments. Electrons have magnetic moments about 6 times larger than protons. If nuclei contain electrons, their magnetic moments should be comparable to electron magnetic moments. Observed nuclear magnetic moments are comparable to proton magnetic moments. Nuclei cannot contain electrons.

Reason 4 - electron- nuclear interactions. The energies binding nuclear particles together are observed to be very large, on the order of 8 MeV per particle. Remember that atomic electronic binding energies are of the order eV to a few keV. Why, then, can some atomic electrons "escape" from being bound inside the nucleus? In other words, if you allow any electrons to be bound inside the nucleus, you really must require all of them to. Of course, it is obvious to us that nuclei don't contain electrons. But that's mainly because we've been taught that way for so long. If we were starting from scratch 60 years ago, we would probably try to "put" electrons inside nuclei.

PROPERTIES OF NUCLEI:

The atomic nucleus is composed of protons and neutrons (Figure 1). Protons and neutrons have approximately the same mass, but protons carry one unit of positive charge +e and neutrons carry no charge. These particles are packed together into an extremely small space at the center of an atom. According to scattering experiments, the nucleus is spherical or ellipsoidal in shape, and about 1/100,000th the size of a hydrogen atom. If an atom were the size of a major league baseball stadium, the nucleus would be roughly the size of the baseball. Protons and neutrons within the nucleus are called nucleons. The atomic nucleus is composed of protons and neutrons. Protons are shown in blue, and neutrons are shown in red.

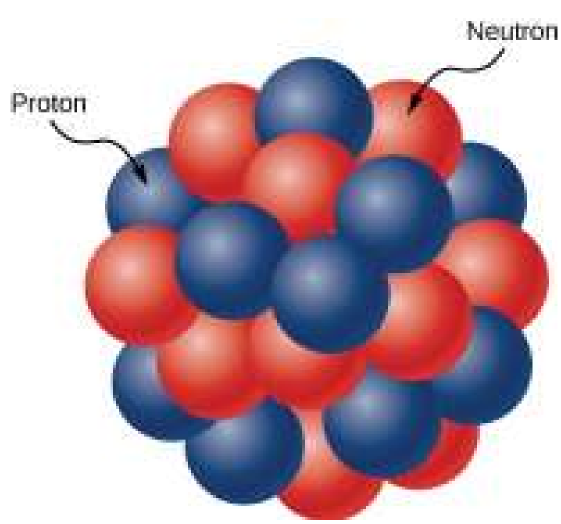


Figure 1: Counts of Nucleons

The number of protons in the nucleus is given by the atomic number, *Z*. The number of neutrons in the nucleus is the neutron number, *N*. The total number of nucleons is the mass number, *A*. These numbers are related by A =Z+N. A nucleus is represented symbolically by ${}^{A}_{Z}X$. Where X represents the chemical element, *A* is the mass number, and *Z* is the atomic number. For example, ${}^{12}_{6}\mathrm{C}$ represents the carbon nucleus with six protons and six neutrons (or 12 nucleons). A graph of the number *N* of neutrons versus the number *Z* of protons for a range of stable nuclei (nuclide**s**) is shown in Figure 2. For a given value of *Z*, multiple values of *N* (blue points) are possible. For small values of *Z*, the number of neutrons equals the number of protons (N=P) and the data fall on the red line. For large values of Z, the number of neutrons is greater than the number of protons N>P and the data points fall above the red line. The number of neutrons is generally greater than the number of protons for Z>15.This graph plots the number of neutrons *N* against the number of protons *Z* for stable atomic nuclei. Larger nuclei have more neutrons than protons.

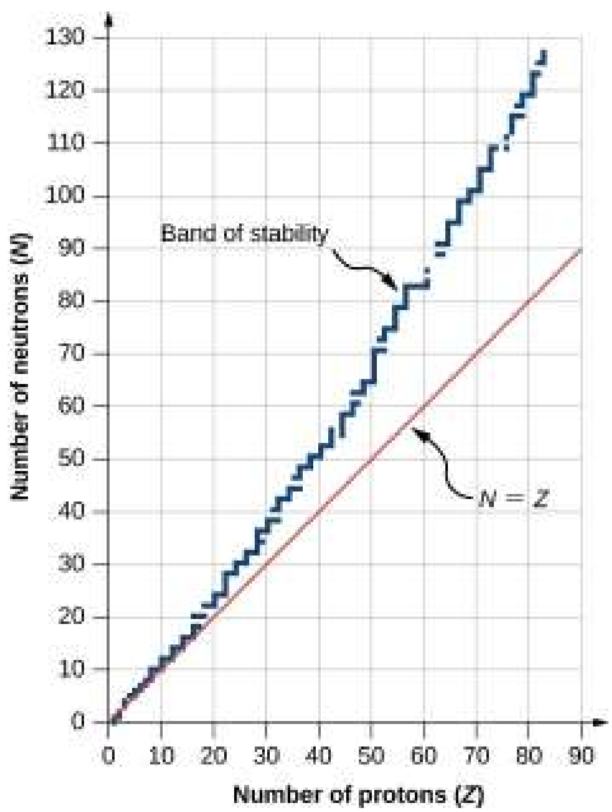


Figure 2: No. of Protons vs No. of Neutrons.

A chart based on this graph that provides more detailed information about each nucleus is given in Figure 3. This chart is called a chart of the nuclides. Each cell or tile represents a separate nucleus. The nuclei are arranged in order of ascending Z (along the horizontal direction) and ascending N (along the vertical direction). For stable nuclei (dark blue backgrounds), cell values represent the percentage of nuclei found on Earth with the same atomic number (percent abundance). For the unstable nuclei, the number represents the half-life.

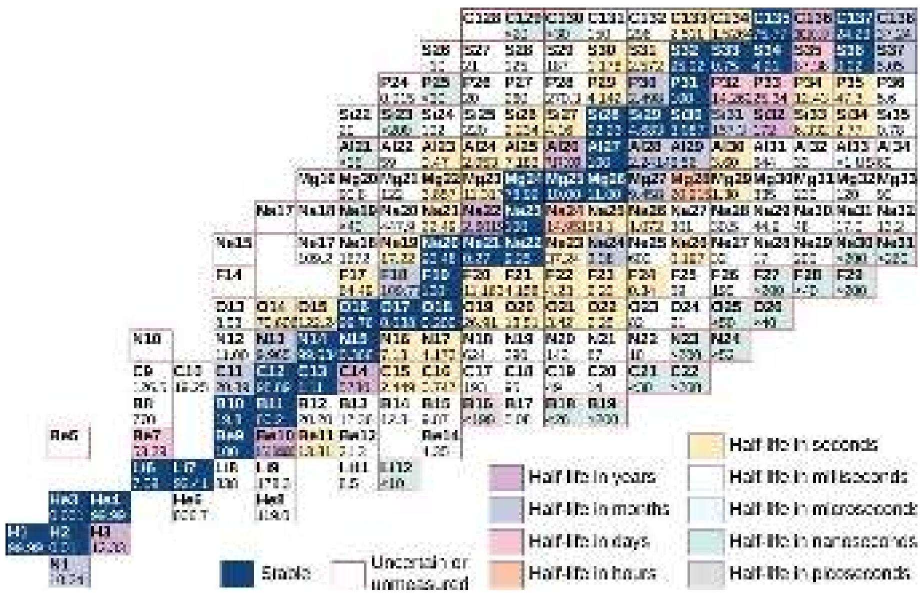


Figure 3: Chart of Nuclei

Atoms that contain nuclei with the same number of protons (Z) and different numbers of neutrons (N) are called isotopes. For example, hydrogen has three isotopes: normal hydrogen (1 proton, no neutrons), deuterium (one proton and one neutron), and tritium (one proton and two neutrons). Isotopes of a given atom share the same chemical properties, since these properties are determined by interactions between the outer electrons of the atom, and not the nucleons. For example, water that contains deuterium rather than hydrogen ("heavy water") looks and tastes like normal water. The following table shows a list of common isotopes.

Why do neutrons outnumber protons in heavier nuclei)? The answer to this question requires an understanding of forces inside the nucleus. Two types of forces exist: (1) the long-range electrostatic (Coulomb) force that makes the positively charged protons repel one another; and (2) the short-range strong nuclear force that makes all nucleons in the nucleus attract one another. We know that there is a “weak” nuclear force existing in nature. This force is responsible for some nuclear decays, but as the name implies, it does not play a role in stabilizing the nucleus against the strong Coulomb repulsion it experiences. Nuclear stability occurs when the attractive forces between nucleons compensate for the repulsive, long-range electrostatic forces between all protons in the nucleus. For heavy nuclei (Z>15) excess neutrons are necessary to keep the electrostatic interactions from breaking the nucleus apart.

(a) The electrostatic force is repulsive and has long range. The arrows represent outward forces on protons (in blue) at the nuclear surface by a proton (also in blue) at the center shown in figure 4.
(b) The strong nuclear force acts between neighboring nucleons. The arrows represent attractive forces exerted by a neutron (in red) on its nearest neighbors.

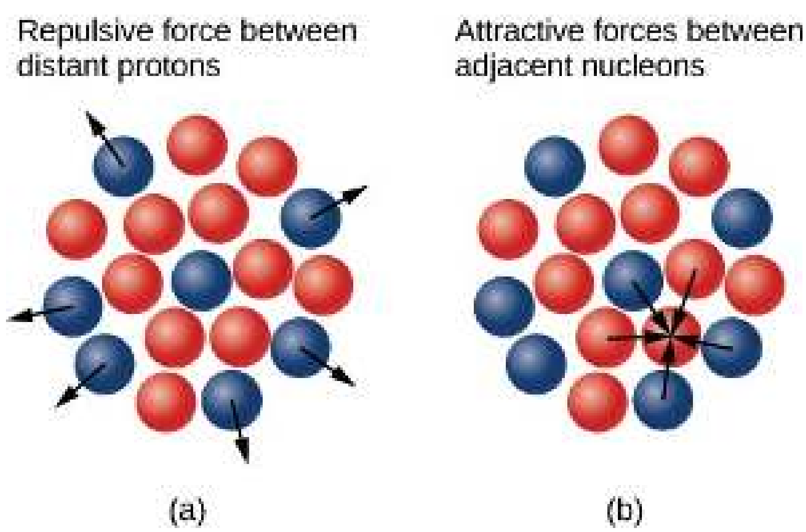


Figure 4

In studying the properties of matter it should be remembered that nuclear and atomic properties are largely decoupled. The electric charge of the nucleus is single determining factor of the atomic structure. All other properties of the nucleus are almost irrelevant to the behavior of the electrons.C^{12} and C^{14} for example are identical in their atomic properties. The nuclear properties of these isotopes are different because of their different nuclear structure. C^{12} is stable while C^{14} is radioactive. The outer nuclear electrons in turn, have no effect on nuclear properties. This delinking of electron and nucleus makes it possible to almost identify all properties of matter either due to atomic part or due to nuclear part but not both. The nuclear is the source of the mass of the atom, its position in the periodic table and its radioactivity, if any. The electrons on the other hand account for all of the physical and chemical properties of the elements and for their characteristic spectra.

NOMENCLATURE:

It is assumed in proton-proton hypothesis that proton and neutron are the two alternative states of a single particle and is given the name nucleon. The two nuclei with same number of protons (Z) and same number of neutrons (N) belong to the same nuclear species i,e a given nuclear species in characterized by charge number Z and mass number A and species is called a nuclide. The species is mentioned as ${}_ZX^A$ where X represents the chemical symbol for an element.

1. Nuclides are classified as nuclides with identical proton number are called isotopes i,e and isotope is one of the several nuclides with same proton number. The examples areH^1, H^2, H^3 and Ca^{40}, Ca^{42} etc.
2. Nuclides with same A but with different Z are called isobars (${}_{20}Ca^{40}$, ${}_{18}A^{40}$ and ${}_{40}Zn^{96}$, ${}_{42}Mo^{96}$, ${}_{44}Ru^{96}$)
3. The nuclides which have same N, the neutron number (A-Z), are called isotones (${}_{19}K^{39}$, ${}_{20}Ca^{40}$ and ${}_{38}Sr^{88}$, ${}_{42}Mo^{92}$).
4. The nuclides with same neutron excess (N-Z) are called isodiapheres (${}_{10}Ne^{22}$, ${}_{8}O^{18}$, and ${}_{20}Ca^{40}$, ${}_{19}K^{38}$).
5. The two nuclides with the same numbers of neutrons and protons but in different energy states in known as isomer. The condition is that at least one of the two energy states must be metastable state.

SIZE OF NUCLEI:

Neutrons and protons are subject to all the four forces in nature, (strong, electromagnetic, weak, and gravity), but the strong force that binds nucleons is an intermediate-range force that extends for a range of about the nucleon diameter (about 1 fm) and then dies off very quickly, in the form of a decaying exponential. The force that keeps the nucleons in a nucleus from collapsing, is a short-range repulsive force that begins to get very large and repulsive for separations less than a nucleon radius, about 1/2 fm.

The *n-n*, *n-p*, and *p-p* nuclear forces are all almost identical. Of course, there is an additional p-p Coulombic repulsive potential, but that is separate from the nuclear force. Owing to these nuclear forces between individual nucleons, a nucleus is tightly bound. The consequence is, from the attractive/repulsive form of the nuclear force that the nucleons are in very close proximity. One can almost imagine a nucleus being made up of incompressible nucleonic spheres, sticking to one other, with a “contact” potential, like ping-pong balls smeared with petroleum jelly. A further consequence of the nuclear force is that nucleons in the nuclear core move, in what seems to be, a constant potential formed by the attraction of its nearby neighbors, only those that are in contact with it. A nucleon at the surface of a nucleus has fewer neighbors, and thus, is less tightly bound.

Nucleons are spin- 1/2 particles (i.e. fermions). Hence the Pauli Exclusion Principle applies. That is, no two identical nucleons may possess the same set of quantum numbers. Consequently, we can “build” a nucleus, much as we built up an atom by placing individual electrons into different quantum “orbitals”, with orbitals being filled according to energy hierarchy, with a maximum of two electrons (spin up and spin down) to an orbital. Nucleons are formed in much the same way, except that all the force is provided by the other constituent nucleons, and there are two different “flavors” of nucleon, the neutron and the proton.

So, it seems that we could build a nucleus of almost any size, were it not for two physical facts that prevent this. The Pauli Exclusion Principle prevents the di-nucleon from being bound. Thus, uniform neutron matter does not exist in nature, except in neutron stars, where gravity, a long-range force, provides the additional binding energy to enable neutron matter to be formed. Thus, to build nuclei, we need to add in approximately an equal proportion of protons. However, this also breaks down because of Coulomb repulsion, for A (the total number of nucleons) greater than about 200 or so.

Moderate to large size nuclei also have more neutrons in the mix, thereby pushing the protons farther apart. It is all a matter of balance, between the Pauli Exclusion Principle and the Coulomb repulsion. And, that balance is remarkably delicate. The di-neutron is not bound, but just not bound. The deuteron is bound, but only just so. The alpha particle is tightly bound, but there are no stable A = 5 nuclei. ^5He (2p + 3n) has a half-life of only 7.9×10^{-22} seconds, while ^5Li (3p + 2n) has a half-life of only $\approx 3 \times 10^{-22}$ seconds. Those lifetimes are so short, that the unbalanced nucleon can only make a few orbits of the nucleus before it breaks away. Nature is delicately balanced, indeed. Since we have argued that nuclei are held together by a "contact" potential, it follows that nuclei would tend to be spherical in "shape", and hence it is reasonable to make mention of .

NUCLEAR SPIN AND ANGULAR MOMENTUM:

The advent of the instruments of high resolving power revealed that when each multiple line was examined with the help of these instruments it was found that each of these multiple lines consist of many lines lying extremely closed together. This new structure of spectral lines was named in atomic physics as hyperfine structure. The order of separation of lines was $1cm^{-1}$ and it was not possible to account this observed fact in term of the properties of extra nuclear electrons. In 1924 Pauli suggested angular momentum for the nucleus in order to explain hyperfine structure of spectral lines. There are other evidences which lead to the assumption of angular momentum for the nucleus, as for example, alternative intensities in band spectra, existence of ortho and para hydrogen.

Now it is quite logical to endow the particles of finite dimensions with an intrinsic spin like the extra nuclear spining electrons. Thus the intrinsic angular momentum of protons or neutrins is $1/2\hbar$. The components of this intrinsic angular momentum are described by $1/2\hbar$ or $-1/2\hbar$ depending upon whether the spin is parallel or anti-parallel to the given direction. I addition each nucleon may be pictured having an angular momentum associated with orbital motion within the nucleus. The evidences such as α-ray and γ-ray spectra, resonance disintegration with slow neutron reveal that constituent particles inside the nucleus are in incessant random motion in discrete quantized orbits. The orbital angular momentum is an integral multiple of ħ. Thus the total angular momentum of a nucleon is the combined effect of its spin contribution and orbital contribution. In terms of quantum numbers, we can write;

$$i = l \pm s$$

(In practice j is used in place of *i)*.

For nuclei containing more than one electron, the above relation is

$$I = L \pm S$$

The orbital angular momentum L is an integral multiple of ħ, S is an even half integral multiple of ħ if the number of nuclear particles in even, and odd half integral if number of particles is odd. This makes total angular momentum I of a nucleus as an integral multiple of ħ when A is even and odd half integral multiple when A is odd. Mathematically the magnitude of angular momentum is Iħ or more correctly $\hbar\sqrt{[I(I+1)]}$. if the component of the total angular momentum vector is measured along ay preferred direction, then possible values are I, (I-1), ……-1, in all (2I+1) values. The component along preferred direction is denoted by m_I (magnetic quantum number) and has (2I +1) values.

In colloquial language of nuclear physics the total angular momentum (I) of a nucleus is preferred as its spin even though it include orbital and spin contributions. It is unfortunate technology and was introduced when internal nuclear structure was not of interest. It is still retained in most of the literature on nuclear physics.

It should be remembered that the total angular momentum of a nucleus in an excited state is different from the one in the ground state. The reason is that in excited state we may have different angular momentum or different orientation with respect to intrinsic spins. Each of these effects changes the total angular momentum by an integral multiple of ħ.

Experimental observations reveal that all nuclei have relatively low spins in their ground states. Although all the nucleons have angular momenta of at least 1/2ħ. The largest measured value is 9/2 with two exception; I is 6 for V^{50} (Vanadium) and 7 for Lu^{176} (Lutetium). This implies that the motion of the nucleons and orientation of their spins are such that most of the angular momentum vectors cancel each other. It is observed that all nuclei with even mass number A and have zero angular momentum with the exceptions of odd-odd nuclei $_1H^2$, $_3Li^6$, $_5B^6$, and $_7N^{14}$. The above results suggest that the nuclear angular momenta cancel in pairs for each type of nucleons. For nuclide the resultant angular momentum is the contribution due to last unpaired particle and incase of odd-odd nuclide the resultant comes for the last proton and last neutron.

The idea that each nucleon has a constant angular momentum means that each nucleon follows a prescribed orbit and does not exchange angular momentum when it encounters with other nucleons. The conservation of angular momentum is an approximat ion to the truth and suffices to explain the basic properties of nucleons.

NUCLEAR MAGNETIC MOMENTUM:

When a charged particle moves in a closed path, it produces both angular momentum and a magnetic field. The magnetic field at large distances may be described as due to magnetic dipole located at the centre of current loop. Thus the angular and spin angular momenta of protons produce extra nuclear magnetic field which can be assumed as due to magnetic dipole located at the centre of the nucleus.

To define magnetic moment we consider a charge particle of mass M and charge e. when harge revolves in a circular orbit it is equivalent to a current of the strength

$$i = e\omega/2\pi \qquad (1)$$

where ω is the angular frequency of the revolution. The magnetic field of this current is equivalent to that of the magnetic dipole moment of the value

$$\mu = \pi r^2 i \qquad (2)$$

where r is the radius of the circular path. The orbital angular momentum of the particle is $\hbar\sqrt{[l(l+1)]}$ and its component in the direction of the magnetic field is quantized. Thus the angular momentum is

$$Mr^2\omega = m_l \hbar \qquad (3)$$

Where m_l is the projection of l in field direction. The maximum value of magnetic moment along the direction due to orbital motion is given by $ml = l$.

$$\mu_{max}\ (\text{orbital}) = e\hbar l/2M \qquad (4)$$

And due to intrinsic spin

$$\mu_{max}\ (\text{spin}) = e\hbar s/M \qquad (5)$$

The equations (4) and (5) result by employing equations 1, 2, and 3. The spin angular momentum is twice as large as the expected value because spin frequency is double than that of orbital frequency. It should be note that it is μ_{max} which is generally measured and therefore subscript is dropped.

It is known that the total angular momentum of the nucleus is contribution due to orbital and spin motions and that is why the magnetic dipole moment is conveniently written as

$$\mu = \mu_N g_N I \qquad (6)$$

where g_N is the nuclear g factor and $\mu = \hbar e/2M_P$ nuclear magnetron with Mp as proton rest mass, its numerical value is 5.051 x 10^{-27} joule/Tesla, μ is vector in a direction of I. the maximum observable component of μ is known as magnetic moment of the nucleus and is represented as

$$\mu = \mu_N g_N \mathrm{I} \qquad (7)$$

it should be noted that this is value of magnetic moment which is measured experimentally and is nuclear magnetic moment.

NUCLEAR STABILITY:

A major concept to remember: "Nature seeks the lowest energy state". In the lowest energy state, things are most stable…less likely to change. Stable atoms have low energy states.

All nuclei are composed of two basic particles, neutrons and protons. Neutrons and protons are almost the same size but differ in their electrical charge. Neutrons have no electrical charge and contribute only mass to the nucleus. Each proton has a positive charge equal in strength to the negative charge carried by an electron. The number of protons in a nucleus is the atomic number (Z) and establishes the chemical identity of the atom. Each atomic number corresponds to a different chemical element; there are now approximately 106 known chemical elements that correspond to nuclei containing from 1 to 106 protons. Because of their very small size it is not convenient to express the mass of nuclei and atomic particles in the conventional unit of kilograms. A more appropriate unit is the atomic mass unit (amu), the reference for which is a carbon atom with a mass number of 12, which is assigned a mass of 12.000 amu. The relationship between the atomic mass unit and kilogram is 1 amu = 1.66 x 10^{-27} kg. The difference in mass between a neutron and proton is quite small: approximately 0.1 %. The larger difference is between the mass of these two particles and the mass of an electron. More than 1,800 electrons are required to equal the mass of a proton or neutron. The total number of particles (neutrons and protons) in a nucleus is the mass number (A, would have been nice if it were called nucleon number). Since neutrons and protons have approximately the same mass, the total mass or weight of a nucleus is, within certain limits, proportional to the mass number. However, the nuclear mass is not precisely proportional to the mass number because neutrons and protons do not have the same mass, and some of the mass is converted into energy when the nucleus is formed ($E= mc^2$). There is a standard method for labeling different nuclear compositions: The mass number is designated by either a superscript preceding the chemical symbol, such as ^{14}C or ^{131}I, or by a number following the symbol, such as C-14, I-131, etc. The atomic number is added as a subscript preceding the chemical symbol. Adding the atomic number to the symbol is somewhat redundant since only one atomic number is associated with each chemical symbol or element. With the exception of the most common isotope of hydrogen, all nuclei contain neutrons and protons. The lighter elements (with low atomic and mass numbers) contain almost equal numbers of neutrons and protons. As the size of the nucleus is increased, the ratio of neutrons to protons increases to a maximum of about 1.3 neutrons per proton for materials with very high atomic numbers. The number of neutrons in a specific nucleus can be obtained by subtracting the atomic number from the mass number. One chemical element may have nuclei containing different numbers of neutrons. This variation in neutron composition usually determines if a nucleus is radioactive. Nuclear stability refers to the tendency of a nucleus of an atom to decay, which means to change into something else. If the isotope of an element (called a nuclide) is unstable (not stable), the nuclide has the tendency of emitting some kind of radiation, and is called radioactive. Radioactivity is associated with unstable nuclides. Carbon-12 is a carbon atom with a total atomic mass of 12. Since carbon can only have 6 protons, carbon-12 must have 6 neutrons (mass of 12 – 6 = 6). Carbon-12 is stable. Carbon-14 is unstable and has 8 neutrons (mass of 14 – 6 = 8). Therefore we may write the conclusion as;

Stable nucleus – non-radioactive
Unstable nucleus – radioactive
Also-- less stable means more radioactive and more stable means less radioactive.

Then what make the nucleus stable?

The major underlying reason is: “Nature seeks the lowest energy state”. In the lowest energy state, things are most stable…less likely to change. One way to view this is that energy makes things happen. If an atom is at its lowest energy state, it has no energy to spare to make a change occur. Think of yourself when you are tired and ready for sleep. In this case you will most likely just stay put and not do anything. The following information that talks about stability is all based on the nucleus tending towards the lowest energy state. Stable atoms have low energy states. Unstable atoms will try and become stable by getting to a lower energy state. They will typically do this by emitting some form of radioactivity and change in the process. The three main forms of radioactive changes are named after the first three Greek letters: alpha, beta and gamma.

Science still does not completely understand why certain isotopes are more stable than others. There are some new theories, and many general observations based on the available stable isotopes. The most important concept, as was stated earlier, that governs stability is that the most stable state is the one with the lowest energy. The nucleus of a given isotope (called a nuclide) will do various things to get to the stable state. You might wonder what forces are working in the nucleus to hold or not hold the protons and neutrons together. There are three forces which are playing their role to stabilize the nucleus. The positive charges of the protons tend to force the protons apart. This is called the electromagnetic force. There is a more mysterious force called the “strong force” that attracts the protons to each other. This counters the electromagnetic force. There is also another mysterious force called the “weak force” that governs how an unstable nucleus will decay into a stable nucleus.

There are some observations that have been made to help us make predictions on what nuclides will be unstable. They are as;

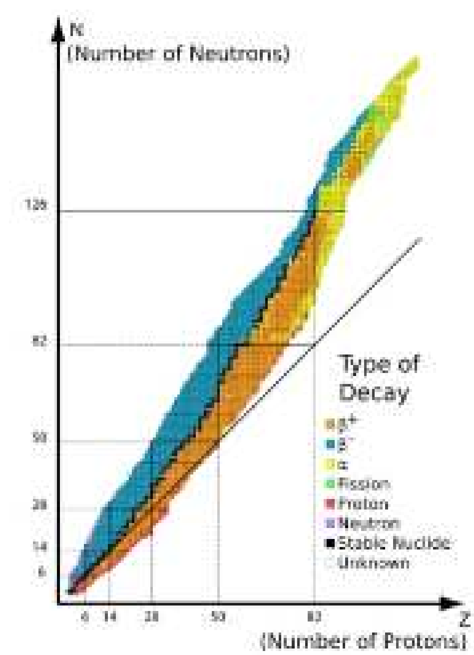
Neutron to proton ratio:

The ratio of neutrons to protons (n/p) is a successful way in predicting nuclear stability. This ratio is close to 1 for atoms of elements with low atomic numbers (of less than about 20 protons). The n/p ratio steadily increases as the atomic number increases past element 20 (calcium) to about element 84 (polonium). Every element beyond an atomic number of 84 is unstable. The strong nuclear force exerts an attractive force among nucleons. The more protons packed together, the more neutrons are needed to bind the nucleus together. Atomic nuclei with atomic numbers up to 20 have almost equal number of protons and neutrons. Nuclei with higher atomic numbers have more neutrons to protons. The number of neutrons needed to create a stable nucleus increases more than the number of protons. Then how do we predict the nuclear stability? One of the simplest ways of predicting the nuclear stability is based on whether a nucleus contains an odd/even number of protons and neutrons as mentioned in table below:

Protons	**Neutrons**	**Number of Stable Nuclides**	**Stability**
Odd	Odd	4	Least Stable
Odd	Even	50	More stable
Even	Odd	57	Even more stable
Even	Even	168	Most stable

Stability:

- Nuclides containing odd numbers of both protons and neutrons are the least stable and this means more radioactive.
- Nuclides containing even numbers of both protons and neutrons are most stable and this means less radioactive.
- Nuclides contain odd numbers of protons and even numbers of neutrons are less stable than nuclides containing even numbers of protons and odd numbers of neutrons. In general, nuclear stability is greater for nuclides containing even numbers of protons and neutrons or both.



The diagram shown above is sometimes called the “belt of stability” or “line of stability”. The black jagged line is the most stable region. The straight black line is where proton numbers equal neutron numbers. For the first 20 or so nuclides, the jagged line is very close to the straight line. As nuclides get larger they need more neurons than protons to remain stable, so the jagged line starts getting steeper than the straight line. Nuclei above the belt of stability can lower their ratio and move to the belt of stability by radioactive decay, which converts a neutron to a proton. This increases the number of protons and decreases neutrons and gets the nuclide on the jagged line. The opposite also can happen when the nuclide has too many protons. In this sort of decay, protons are converted to neutrons.

Other observations for prediction:

- Nuclei with 2,8,20,28,50, or 82 protons; or 2,8,20,28,50,82, or 126 neutrons; are generally more stable...magic numbers.
- Nuclei with an even number of protons or neutrons are more stable than those with odd numbers.
- These stability factors have been compared to the stability of 2,8,18,32 in electron shells.

BINDING ENERGY :-

It is known that nucleus consist of large number of particles, namely neutrons and protons. Now the question is "what is the agency that keeps these in a tightly bound structure inspite of the fact that protons are positively charged and repel other protons?". It turns out that particles should be held together by strong attractive forces. This idea is confirmed by the fact that when it is desired to break up a nucleus enormous amount of energy is supplied to the nucleus i.e work is done against the attractive forces. when large amount of energy is supplied to a nucleus the constituents of nucleus are torn apart. It means that the total energy of the constituents is greater than when they form nucleus. Conversely when the nucleons are brought together their total energy is less than the sum of the energies of its constituents when the are held apart. Now the neutral question is what happens to the excess energy? Does it form the origin of attracting forces?

It has been also seen that actual mass of nucleus is always less than the mass of its constituents. where does the mass go? The answer is furnished by famous mass energy relation of Einstein i.e

$$E = mc^2 \quad \text{--- (1)}$$

The above equation states that mass and energy are the manifestations of one and the same thing and one can be converted into other. Thus we can say that mass defect $\Delta_Z M^A$ appears as an equal amount of energy ΔE on forming a nucleus. ΔE is the energy released due to the decrease of mass, when nucleus is formed by fusing together the requisite number of nucleons, alternately it is the energy required to separate the nucleons of nucleus. ΔE is referred as the binding energy (BE) of the nucleus.

The binding energy of a nuclide $_Z X^A$ may be expressed as:

$$B.E = (\Delta_Z M^A)\, c^2$$

$$B.E = \{ZM_p + (A-Z)M_n - ZM^A\}\, c^2 \quad \text{--- (2)}$$

M_p = mass of proton
M_n = mass of neutron
$\Delta_Z M^A = (ZM_p + (A-Z)M_n - ZM^A)$ = Mass defect.

The binding energy per nucleon will be:

$$\frac{B.E}{A} = \bar{B} = \frac{c^2}{A}\left[ZM_p + (A-Z)M_n - ZM^A\right] \quad \text{--- (3)}$$

If masses are in unified mass unit, then

$$\bar{B} = \frac{1}{A}\left\{ZM_p + (A-Z)M_n - {}_Z M^A\right] \times 931.5 \text{ MeV} \quad \text{--- (4)}$$

If M_H is mass of hydrogen atom, M is the mass of corresponding atom, equation (4) may be written as

$$\bar{B} = \frac{1}{A}\left\{Z M_H + (A-Z) M_n - M\right\} \times 931.5 \text{ MeV} \quad \text{--- (5)}$$

In above equation, no account is made of electron binding energy with the nucleus. The variation of binding energy per nucleon with mass number is shown in figure 10. The curve indicates that $\bar{B}$ is very small for very light nuclides. It increases as A increases, reaches a maximum value of about 8.8 MeV for A = 56 (Fe). The maximum is quite flat and $\bar{B}$ is 8.4 MeV. For higher mass number $\bar{B}$ decreases to about 7.6 MeV for uranium. The curve also shows peaks for the nuclides of mass number 4, 8, 12, 16, 20. It is now in brief. desired to explain the above noted features

(a) <u>Small Binding energy in case of light nuclei</u>:-

In case of light nuclei, there are few nucleons and as a result, most of them are at the surface of the nucleus. this surface effect try to disrupt the nucleons and thereby reduces the binding energy of the nucleus. Also that light nuclei have comparatively small dimensions. In any nucleus the rationalized de-Broglie wavelength should be less than the nuclear dimensions. Therefore, in order to keep ƛ small, kinetic energy is large. This makes the binding energy a small quantity because it is the difference of P.E and K.E of the system.

(b) <u>Occurance of peaks in binding energy curve</u>:-

The peaks occur at mass number 4, 8, 12, 16 and 20. Let us take the example of $_2He^4$. He^4 contains the maximum possible number of nucleons, the four particles differing with respect to their two possible spin orientations and two possible values of charge. This brings out zero angular momentum for helium nucleus. It means that there is no centrifugal force to reduce the strength of binding forces and hence He^4 shows a tightly bound configuration associated with maximum value of binding energy. The similar arguments hold good for other tightly ~~st~~ stable nuclei showing peaks.

(C) A constant binding energy per nucleon:

If the energy is expressed in mass units, then binding energy expression is written as;

$$B.E = ZM_H + (A-Z)M_n - M$$

$$= AM_n + (M_H - M_n)Z - M$$

$$\bar{B} = (M_n - 1) + \frac{Z}{A}(M_H - M_n) - \frac{M - A}{A}$$

$$\bar{B} = (M_n - 1) + \frac{Z}{A}(M_H - M_n) - f \quad \text{--- (6)}$$

$$\bar{B} = (1.0086 - 1) - .46 \times 0.00066 - 6 \times 10^{-4}$$

$$= 8.5 \text{ MeV/nucleon}$$

(d) The decrease of binding energy per nucleon for high mass number:

As the value of A further increases, the coulomb repulsion ~~further~~ increases. ~~Furthermore~~ Furthermore, when A is sufficiently large, nuclear forces are saturated and nuclear binding behaves like homopolar binding in chemical system. These two reasons are suffice. to account fall in binding energy per nucleon.

LIQUID DROP MODEL

The liquid drop model of the nucleus as proposed by N. Bohr in 1936 uses the concept of potential barrier developed by Gamow.

According to this model, the nuclei of all the elements behave like a liquid drop of electrically charged, incompressible liquid of constant density but of varying mass. The liquid in reality consists of neutrons and protons.

As a first approximation, we can think of each nucleon in a nucleus as interacting solely its nearest neighbours, like the molecules of a liquid which ideally are free to move about but always maintain a fixed intermolecular distance from their nearest molecules.

ASSUMPTIONS:

The main assumptions of liquid drop model are:

(1) The nucleus is supposed to be spherical in shape in its stable state just as a liquid drop in spherical due to the symmetrical forces of surface tension.

(2) The volume as well as the mass of the ~~molecules~~ nucleus being proportional to the atomic mass number 'A' the density of a nucleus is constant, independent of volume. Similarly, the density of a liquid drop is constant, independent of its volume. [One point of difference should be noted. The density of a nucleus is the same for nuclei of different elements but the density of a liquid is different for different liquids.]

(3) The nucleons are supposed to move about within a spherical enclosure represented by the nuclear potential barrier just as the molecules move about within a spherical drop of the liquid, the shape of which is determined by properties of surface tension.

(4) The two main properties of nuclear forces are their short range and tendency to saturate. These can be deduced from the fact that is the binding energy per nucleon is almost a constant quantity (nearly 8 Mev) for all but the lighter nuclei and, therefore, the total binding energy of the nucleus is proportional to its mass number 'A' i.e. the total number of nucleons. i.e. its the volume of the nucleus is also proportional to the atomic mass.

(5) Just as the latent heat of vaporization is a constant for a liquid, the binding energy per nucleon is also a constant

(6) The molecules evaporate from a liquid drop on raising the temperature of the liquid due to their increased energy of thermal agitation. Similarly when energy is given to a ~~[illegible]~~ nucleus by bombarding it with nuclear projectiles, a compound nucleus is formed which emits nuclear radiations almost ~~[illegible]~~ immediately.

(7) When a small drop of a liquid is allowed to oscillate, it breaks up into two smaller drops of equal size. The process of nuclear fission is similar ~~to~~ and the nucleus breaks up into

two smaller nuclei.

Justification :-

From the above assumptions we find that the properties of a nucleus are very similar to the properties of a liquid drop. Hence it is justified to call this model of the nucleus as liquid drop model.

Meson theory of Nuclear forces:-

It has been mentioned that nuclear forces have, at least in part, an exchange character and are like molecular forces. In molecular ~~forces~~ bonds, the valence electrons are exchanged. Now a natural question is "what is exchanged in nuclear bonds"? is it electron? No, it cannot be, because it leads to very weak interaction. Yukawa in 1935, Proposed that nuclear forces are due to an exchange of particles of intermediate mass, known as mesotrons or mesons (Yukawa particle). Yukawa took the ~~arg~~ analogy from the quantum field theory of electromagnetic field in which photon exchange takes place and gravitational field in which exchange of gravitons is assumed. Both these field particles have zero rest mass, but the nuclear field particle has finite ~~mass~~ rest mass. This is because of the difference that nuclear force is short range force while others are not. The rest mass M_x of the field particle may be computed as follows:

when one nucleon exerts force on the other, meason is created and the creation of meason violates the conservation of energy by the amount ΔE corresponding to meson rest mass i.e

$$\Delta E = M_\pi c^2 \quad — ①$$

The duration of excursion of meson, Δt is given by uncertainity principle

$$\Delta t = \hbar/\Delta E \quad — ②$$

In this time meason can cover a distance r_0, given by

$$r_0 = c\Delta t = \frac{c\hbar}{\Delta E}$$

$$r_0 = \frac{c\hbar}{M_\pi c^2} = \frac{\hbar}{M_\pi c} \quad — ③$$

r_0 is the range of nuclear force and if we put $r_0 = 1.4f$, then

$$M_\pi = \frac{\hbar}{r_0 c} = \frac{1.062 \times 10^{-34}}{1.4 \times 10^{-15} \times 3.0 \times 10^{8}}$$

$$= 0.25 \times 10^{-27} \text{ kg}$$

$$M_\pi = \frac{0.25 \times 10^{-27}}{9.01 \times 10^{-31}}$$

$M_\pi = 270 m_0$; m_0 being the rest mass of electron.

A search for Yukawa particle started soon after its hypothesis and in 1947, Powell et. al., discovered π-meson in cosmic radiations and has a mass of 273 mo. The particle, π-meson is exact Yukawa particle. The pions are of three kinds, positive π^+ negative (π^-) and natural (π^0) all with intrinsic spin $S=0$. Their rest masses are 139.6 MeV., 139.6 MeV and 135.0 MeV respectively. The force field between two protons or two neutrons is carried by a neutral pion while between a neutron and proton by a charged pion.

According to Yukawa's hypothesis, nucleon is regarded as a source of field quanta and hence of the meson field, in the similar fashion as charge is regarded a source of photon field. A nucleon is thought to be surrounded by virtual pions. The meson field possesses a static type of interaction which can be represented by a potential function. An expression for the potential function will be now derived:

The relativistic form of energy E of particle of rest mass M_π and momentum p is given by

$$E^2 = p^2c^2 + M_\pi^2 c^4 \quad — (1)$$

where c is the velocity of light. In quantum mechanics E and p have the operator forms

$$E = i\hbar\frac{\partial}{\partial t} \quad \text{and} \quad p = -i\hbar\nabla \quad — (2)$$

Putting in eqn (1) we have:

$$-\hbar^2\frac{\partial^2}{\partial t^2} = -\hbar^2c^2\nabla^2 + M_\pi^2c^4 \quad — (3)$$

If ϕ is pion wave function then wave equation for pion takes the form

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{M_\pi^2c^2}{\hbar^2}\right)\phi = 0. \quad — (4)$$

This is Klein Gordon equation for a free particle of spin zero. If we set $M_\pi = 0$, we get

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \quad — (5)$$

This is wave equation for electromagnetic field. Thus eqn (4) may be thought as derived from eqn (1). Now the simplest type of EM field is electrostatic field.

The corresponding eqn is obtained by putting $\frac{\partial \phi}{\partial t} = 0$ i.e.

$$\nabla^2 \phi = 0 \text{ : laplace equation.}$$

The identical equation for meson field is

$$\left(\nabla^2 - \frac{m_\pi^2 c^2}{\hbar^2}\right)\phi = 0 \quad \text{— (6)}$$

This is in absence of any source of mesons, but in the presence of source, the equation should resemble with poisson's equation i.e. it should have the form.

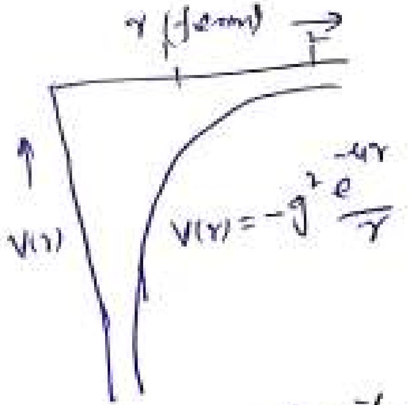
$$(\nabla^2 - \mu^2)\phi = 4\pi g\,\delta(r) \quad \text{— (7)}$$

where $\mu = \frac{m_\pi c}{\hbar} = \frac{1}{r_0}$. The factor 'g' plays the same role as the charge 'e' plays in the case of electrostatic field, of nuclear field and is known as and is a measure of meson charge. $\delta(r)$ is dirac delta function [$\delta(r) = 1$ at $r = 0$ $\delta(r) = 0$ at finite r]. The solution of eqn (7) comes out to be

$$\phi = g\frac{e^{-\mu r}}{r} \quad \text{— (8)}$$

And the meson potential will be

$$V(r) = g\phi = g^2\frac{e^{-\mu r}}{r} \quad \text{— (9)}$$



Yukawa potential.

Gamow's theory of α-decay :

This theory was developed in 1928 by Gamow in Collaboration with Gurney and condon. According to this theory :

1. A α-particle may exist as an entity within the heavy nucleus.
2. The α-particle is in constant motion and is contained in the nucleus by the surrounding potential barrier. If bounces back and forth from the barrier walls. On each collision with the "wall" there is a definite probability given by the equation $T = e^{-2k_2 a}$ (know as Transmission probability) that the particle will leak through the barrier. In fact, the α-particle within the nucleus must present itself again and again at the barrier surface until conditions are ripe for penetration or leakage. In $_{92}U^{238}$ the particle must make 10^{38} tries i.e 10^{22} tries per second for 10^{16} seconds or 10^{9} years before it escapes.

Let v be the frequency with which the α-particle collides with the walls in order to escape from the nucleus and T the Transmission (coefficient) ~~prof~~ probability in each collision. Then

Radioactive constant λ = decay probability per unit time

$$= vT. \quad \text{———} (1)$$

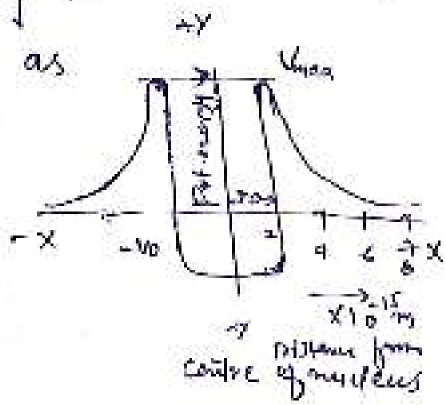
Suppose at any time only one α-particle exists as such in the nucleus and that it moves back and forth along the nuclear diameter then ;

$$\nu = \frac{v}{2r_0} \quad —(2)$$

Where v is the velocity of the α-particle when it eventually leaves the nucleus and r_0 is the nuclear radius. Hence

$$\lambda = \frac{v}{2r_0} T. \quad —(3)$$

The value of Transmission probability for a barrier of constant height V_0 and width 'a' as



$$T = e^{-2k_2 a}$$

Where $$K_2 = \sqrt{\frac{2m(V_0-E)}{\hbar}} \quad —(4)$$

But an α-particle within the nucleus has to overcome a barrier of varying height. as shown in fig. ~~as shown~~ As the potential is not constant in the region $x = r_0$ to $x = r$, we can divide it in a series of small steps each of thickness dx, then the probability of transmission through a small thickness dx is given by

$$T = e^{-2k_2(x)dx} \quad —(5)$$

The total probability is the product of individual probabilities of all small steps from $x = r_0$ to $x = r_1$.

Hence $$T = e^{-2\int_{r_0}^{r_1} K_2(x)\,dx}$$

or $$\ln T = -2\int_{r_0}^{r_1} K_2(x)\,dx \quad —(6)$$

r_1 is the distance from the centre of the nucleus where $V_x = E$. The kinetic energy E is greater than the potential energy V_x for values of $x > r_1$. So if the α-particle can get past r_1, it will permanently the escape from the nucleus.

Now $V_x = \dfrac{2Ze^2}{4\pi\varepsilon_0 x}$ — (7), where Z is the atomic number of the daughter nucleus.

$$\therefore \quad k_2(x) = \frac{\sqrt{2m(V_x - E)}}{\hbar} = \left(\frac{2m}{\hbar^2}\right)^{1/2}\left[\frac{2Ze^2}{4\pi\varepsilon_0 x} - E\right]^{1/2} \quad \text{— (8)}$$

As $V_x = E$, when $x = r_1$

$$E = \frac{2Ze^2}{4\pi\varepsilon_0 r_1} \quad \text{— (9)}$$

$$\therefore \quad \frac{2Ze^2}{4\pi\varepsilon_0 x} = \frac{2Ze^2}{4\pi\varepsilon_0 r_1}\cdot\frac{r_1}{x} = E\frac{r_1}{x}.$$

Substituting in equation (8) we get.

$$k_2(x) = \left(\frac{2mE}{\hbar^2}\right)^{1/2}\left[\frac{r_1}{x} - 1\right]^{1/2}$$

$$\text{and } \ln T = -2\int_{r_0}^{r_1} k_2(x)\,dx = -2\left(\frac{2mE}{\hbar^2}\right)^{1/2}\int_{r_0}^{r_1}\left(\frac{r_1}{x} - 1\right)^{1/2} dx. \quad \text{— (10)}$$

To evaluate the integral put $\dfrac{x}{r_1} = \cos^2\phi$

or
$$x = r_1\cos^2\phi$$
$$dx = -2r_1\cos\phi\sin\phi\,d\phi$$

Hence
$$\left(\frac{r_1}{x} - 1\right)^{1/2} dx = -\left(\frac{1}{\cos^2\phi} - 1\right)^{1/2}\cdot 2r_1\cos\phi\sin\phi\,d\phi.$$
$$= -2r_1\sin^2\phi\,d\phi = -r_1(1 - \cos 2\phi)\,d\phi$$

$$\therefore \quad \int_{r_0}^{r_1}\left(\frac{r_1}{x} - 1\right)^{1/2} dx = -r_1\int_{r_0}^{r_1}(1 - \cos 2\phi)\,d\phi$$

$$= -r_1\left[\phi - \frac{\sin 2\phi}{2}\right]_{r_0}^{r_1} = -r_1\left[\phi - \sin\phi\cos\phi\right]_{r_0}^{r_1}$$

$$= r_1\left[\cos^{-1}\left(\frac{r_0}{r_1}\right)^{1/2} - \left(\frac{r_0}{r_1}\right)^{1/2}\cdot\left(1 - \frac{r_0}{r_1}\right)^{1/2}\right]$$

$$\therefore \quad \ln T = -2\left(\frac{2mE}{\hbar^2}\right)^{1/2} r_1\left[\cos^{-1}\left(\frac{r_0}{r_1}\right)^{1/2} - \left(\frac{r_0}{r_1}\right)^{1/2}\left(1-\frac{r_0}{r_1}\right)^{1/2}\right] \quad \text{—(11)}$$

Since the barrier is relatively wide $r_1 >> r_0$

$$\therefore \quad \cos^{-1}\left(\frac{r_0}{r_1}\right)^{1/2} = \frac{\pi}{2} - \left(\frac{r_0}{r_1}\right)^{1/2} \quad \text{and} \quad \left(1-\frac{r_0}{r_1}\right)^{1/2} = 1$$

Substituting in equation (11), we get.

$$\ln T = -2\left(\frac{2mE}{\hbar^2}\right)^{1/2} r_1\left[\frac{\pi}{2} - 2\left(\frac{r_0}{r_1}\right)^{1/2}\right]$$

From equation (9) $\quad r_1 = \dfrac{2Ze^2}{4\pi\varepsilon_0 E}$

$$\text{Hence } \ln T = -2\left(\frac{2mE}{\hbar^2}\right)^{1/2}\left[r_1\frac{\pi}{2} - 2(r_0 r_1)^{1/2}\right]$$

$$= -2\left(\frac{2mE}{\hbar^2}\right)^{1/2}\left[\frac{Ze^2}{4\varepsilon_0 E} - 2\left(\frac{r_0 Ze^2}{2\pi\varepsilon_0 E}\right)^{1/2}\right]$$

$$= \frac{4e}{\hbar}\left(\frac{m}{\pi\varepsilon_0}\right)^{1/2} Z^{1/2} r_0^{1/2} - \frac{e^2}{\hbar\varepsilon_0}\left(\frac{m}{2}\right)^{1/2} Z E^{-1/2} \quad \text{—(12)}$$

Now $\dfrac{4e}{\hbar}\left(\dfrac{m}{\pi\varepsilon_0}\right)^{1/2} = 2.97$ and $\dfrac{e^2}{\hbar\varepsilon_0}\left(\dfrac{m}{2}\right)^{1/2} = 3.95$

$$\therefore \quad \ln T = 2.97\, Z^{1/2} r_0^{1/2} - 3.95\, Z E^{-1/2}$$

where r_0 is in fermi (10^{-15} m) and E is in MeV. The radioactive constant

$$\lambda = \frac{v}{2r_0} T$$

$$\therefore \ln \lambda = \ln\left(\frac{v}{2r_0}\right) + \ln T$$

$$= \ln\left(\frac{v}{2r_0}\right) + 2.97\, Z^{1/2} r_0^{1/2} - 3.95\, Z E^{-1/2}$$

$$\text{or} \quad \log_{10}\lambda = \log_{10}\left(\frac{v}{2r_0}\right) + 1.29\, Z^{1/2} r_0^{1/2} - 1.72\, Z E^{-1/2}.$$

BETA - DECAY :

The β-particles emitted in radioactive decay of heavy nuclei are ordinary electrons having same charge and mass values. However, the expression β-decay now covers all such phenomena in which a nucleus makes an isobaric transition due to natural or induced radioactivity by the emission of an electron (β^-) or a positron (β^+) or electron capture i/e capture of an orbital electron. An electron or a positron does not exist in the nucleus. An electron is produced by the spontaneous conversion of a neutron into a proton where as a positron is produced due to the spontaneous conversion of a proton into a neutron. Thus in β-decay the mass number remains the same but the charge number changes by one i/e from Z to (Z+1) in the case of β^- emission and from Z to (Z-1) in the case of β^+ emission or electron capture. As the mass of the electron is nearly 1/7000 times the mass of an α-particle, the energy of the β-particle is very small, usually less than 4 MeV though their velocities are as high as 0.995c.

β-ray energy spectrum :-

The energy spectrum of β-particles has been studied with the help of a magnetic spectrometer shown in

Figure below. the β-particle emitted by the radioactive source R placed in a cavity in a block of lead inside a highly evacuated box are deflected into a circular path by a magnetic field perpendicular to the plane of the paper in accordance with the equation

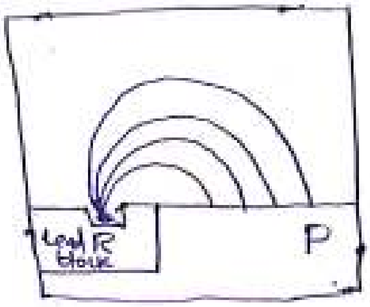
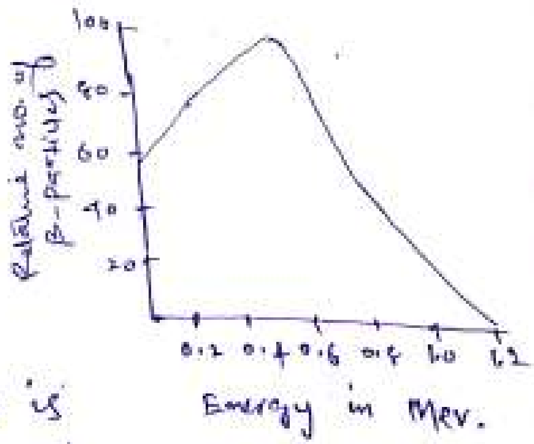


Figure.

$$Bev = \frac{mv^2}{R}$$

where B is the intensity of the magnetic field, 'e' the charge. m' the mass. v the velocity of the β-particle and R the radius of the path. Thus particles of different energies (or velocities) are focused at different points. these are recorded on a photographic plate and form the photographic impression, the relative number of β-particles and their energies can be determined. A graph is plotted between relative number of β-particles and their energies can be determined. A graph is plotted between relative number of β-particles and energy in Mev as shown in figure below.



End point energy:

The β-spectrum is continuous, having energies ranging from zero to a certain ~~value~~ well defined limit known as End Point energy, which is a characteristic of the β-emitter. The energy distribution has a well defined maximum the height and position of which also depends upon the nature of the radioactive substance emitting the β-particles.

Thus the end point energy is the maximum energy with which a β-particle is emitted from a radioactive nuclide.

β-Spectrum discrete or continuous:-

β-Spectrum is continuous having energies ranging from zero to a certain well defined maximum limit known as end point energy. The β-ray energy spectrum produced by naturally radioactive elements as source is also found to exhibit a series of lines superimposed on the continuous spectrum as background. These sharp lines of the β-spectrum with discrete energies are due to the electrons that have been ejected from K, L, M, and N shells of the atom due to the phenomenon of internal conversion.

Theory of γ-emission:

The emission of α or β-particles from naturally radioactive substances is invariably followed by emission of γ-rays. The emission of an α or a β-particle from a radioactive substance may leave the daughter nuclei in one or more excited states. When the nucleus in excited ~~state~~ state passes to the ground state or to a lower excited state from a higher excited state, it emits a high energy photon. This photon emitted from nucleus in an excited state is known as γ-ray. It is found that $_{83}Bi^{212}$ decays to $_{81}Tl^{208}$ by α-emission in 34% cases and to $_{84}Po^{212}$ by β-emission in 66% cases, in both the cases the daughter nucleus may exist in the ground state or in one of the excited states. When the nucleus exists in the excited state, it emits a γ-ray and passes to a lower energy state or the ground state. All the transitions from one level to the other, however, do not take place, as some are forbidden by certain ~~sto~~ selection rules. The γ-emission must satisfy the following conservation laws:

1) Conservation of charge & Nucleon Number:- In γ-emission the daughter nucleus and the parent nucleus are exactly identical except for the difference in excitation energy. ~~The~~ Hence the charge and the nucleon number remains the same. Emission of a γ-ray photon is represented by the equation

$$ {}_Z^{*}X^A \rightarrow {}_ZX^A + \gamma , $$ where ${}_Z^{*}X^A$ represents the excited state of the nucleus & ${}_ZX^A$ the ground state.

2) Conservation of mass energy:- If the transition takes place from an excited nuclear energy state E_2 to a lower energy state E_1, then $E_2 - E_1 = h\nu$, where ν is frequency of γ-ray photon.

3) Conservation of Linear & Angular momentum:- The linear momentum associated with the γ-ray photon is $\frac{h\nu}{c}$, hence the emission of a γ-ray must make the daughter nucleus recoil with the same momentum in the opposite direction if the parent nucleus is at rest. If M is the mass and V the velocity of the daughter nucleus, then

$$ \frac{h\nu}{c} + MV = 0 . $$

In addition, the angular momentum must also be conserved. It should be noted that the intrinsic angular momentum or the spin of the photon $= \frac{h}{2\pi} = \hbar$.

NUCLEAR REACTION CROSS-SECTION:

Nuclear cross section is a convenient way to express the probability that a bombarding particle will interact in a certain way with a target particles. It is supposed that each target particle presents a certain area known as its cross-section to the incident particles. Any incident particle that directed at this area interacts with the target particle. Hence the greater the cross section greater is the likelihood of interaction. The nuclear reaction cross-section may be defined as;

i) The probability that an event may occur when a single nucleus is exposed to a beam of particles of total flux one particle per unit area.

OR

ii) The probability that an event may occur when a single particle is shot perpendicularly at a target consisting of one particle per unit area.

Determination of Cross-section: Suppose we have a slab of some material whose area is *A* and whose thickness is *dx*, then the Volume of slab = *Adx*. Let the material contain n atoms per unit volume, then total number of nuclei in the slab = *nAdx*. Further we assume that each nucleus has a cross section σ for some particular interaction, then aggregate cross section for all the nuclei in the slab = *σnAdx*.

Let N be the number of incident particles in a bombarding beam and dN the number of particles that interaction with nuclei in the slab, then;

$$\frac{Number\ of\ interacting\ particles}{Number\ of\ incident\ particles} = \frac{Aggregate\ cross-section}{Target\ area}$$

Or $$\sigma = \frac{dN/N}{ndx}$$

Here σ gives the cross-section per nucleus or microscopic cross-section.

TYPES OF INTERACTIONS:

Prior to classifying the elementary particles, knowledge of various types of interactions between then is essential, because it will furnish information about their properties and decay modes. These interactions fall into following four categories, mentioned below in order of decreasing strength.

a) ***Strong Interaction***: in order to hold nucleus together even with strong repulsive force existing between them, strong force of nuclear origin is needed. This force is independent of electric charge, and cannot be described in terms of a strength-distance relationship. These are sort range forces. This type of force cannot be of any other origin because of force of other origin would fail to supply the necessary binding energy. Strong interaction is thus n the forces which hold nucleons together in the nuclei of atoms. The range of strong interaction in limited to about 2 x 10^{-13} cm. time interval of such an interaction is roughly 10^{-23} sec. other strong interaction processes are the scattering of mesons, nucleons by nucleons, the formation of new particles by reactions between such particles and the decay of certain type of particles. Resonant states originate and decay as a result of strong interaction.

b) ***Electromagnetic interaction***: It operates on all charged particles and provides the atomic and molecular binding forces. This electromagnetic interactions are charge dependent (attractive as well as repulsive). Other examples of such type of interaction are the pair formation of photons and vice-versa, and the decay of a neutral pion into two gamma ray photons. This type of interaction is about 10^{-3} parts of the strong interaction. The characteristic time is 10^{-20} sec.

c) ***Weak interaction***: All strong interactions take place in times of about 10^{-23} sec. Yet it has been observed that some of the resulting particles, although energetically unstable, suffer no decay until a time 10^{13} time greater than 10^{-23} is reached. That is their decay takes place in time of about 10-10 sec. For example, β-decay of radioactive nuclei does not take place until a time 10^{13} times greater than that involved in strong interaction has approached. Had there been strong nuclear or electromagnetic interaction, there would have been no such delay in the decay process. Therefore this delay in decay process suggests that either these particles are not subjected to strong interacting forces or there is some new conservation law or prohibition which forbids the decay. But since most of the particles involved are subjected to either the nuclear force or have electric charge or both, there must be some rule which stops the process. But eventually the decays do happen, there must be some other type if interaction as predicted by Fermi in the early 1930s to explain β-decay. Since particles take long time to respond to such an interaction, force involved must be very weak compared with strong nuclear forces. The range of such an interaction is perhaps less than 10^{-13} cm and is consequently, termed as weak interaction. The characteristic time of such interaction is of the order of 10^{-10} sec.

d) ***Gravitational Interaction***: it is the weakest of the four types of interactions. It has an infinite range but it is weaker than the strong interaction in a proportion of roughly 10^{-39}. It has a great influence on the macroscopic behavior of the matter but for atoms and sub-nuclear particles its effect is negligible. As photon is the agent of electromagnetic field, in a similar way gravitation can be explained in terms of the interactions of '*gravitons*'. Their mass must be zero and therefore the velocity must be that of light.

CLASSIFICATION OF ELEMENTARY PARTICLES

Early in 1930, the electron and the proton were recognized as constituents of all the elements and hence were regarded as elementary or fundamental particles. The neutron and the positron were discovered in 1932 and the neutrino in 1934. Various types of mesons were discovered in the study of cosmic rays. All these particles are now considered as elementary of fundamental, in the sense that "It has not been proved possible, profitable or useful to regard these as made up of something else".

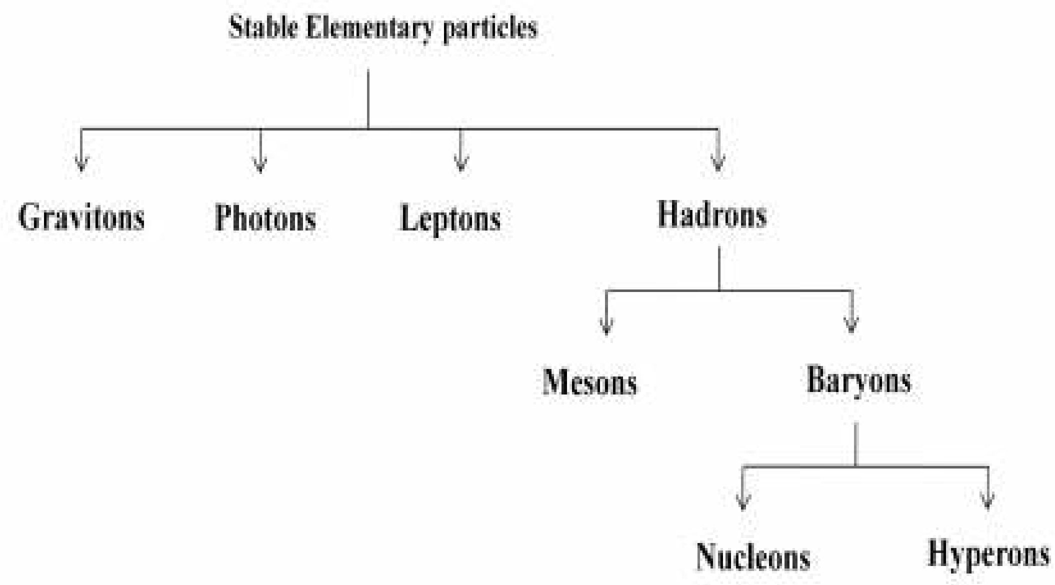
CLASSIFICATION:

Particles having their half-life $\tau_{1/2} \geq 10^{-16}$ sec are known as stable particles and those having half-life $\tau_{1/2} \sim 10^{-22}$ sec are known as resonances. There are 35 known stable elementary particles. These have been classified into 4 groups in accordance with four types of interactions namely;

i) Gravitational ii) Electromagnetic iii) Weak interaction and iv) Strong interaction.

These are i) Gravitons ii) Photons iii) Leptons and iv) Hadrons.

The hadrons are further divided into two groups a) Mesons and b) Baryons. The mesons have masses intermediate between muons (μ-mesons) and nucleons and baryons include nucleons and the particles heavier than nucleons known as hyperons. All these classes of particles are shown as;



Anti-particles: All elementary particles have their anti-particles. An anti-particle is a particle having the same mass, spin and life time (if unstable) but its charge (if any) has the opposite sign and the alignment or anti-alignment between its spin and magnetic moment is also opposite to that of the particle.

All particles, including photons and neutrinos, participate in gravitational interactions. The photon can interact electromagnetically with any particle that carries electric charge. All charged leptons participate both in the weak and electromagnetic interactions, and neutral leptons, of course, have no direct electromagnetic coupling. (This is what made it so difficult to observe the neutrino in β decay.) Leptons do not sense the strong force. All hadrons (mesons and baryons) respond to the strong force and appear to participate in all the interactions. The common characteristic of mesons and baryons is that they appear to have substructure, and a size of the order of one femtometer. All the particles in nature can be classified as either bosons or fermions, with the basic difference between them being the statistics that they obey. Bosons obey Bose-Einstein statistics whereas fermions satisfy Fermi-Dirac statistics. This is reflected in the structure of their wave functions. For example, the quantum mechanical wave function for a system of identical bosons is symmetric under the exchange of any pair of particles. That is,

$$\psi_B(x_1, x_2, x_3 \ldots, x_n) = \psi_B(x_2, x_i, x_3, \ldots, x_n) \qquad (1)$$

where the x_i denote, collectively, space-time coordinates as well as internal quantum numbers of particle i. On the other hand, under similar assumptions, the quantum mechanical wave function for a system of identical fermions is antisymmetric under the exchange of any pair of particles, namely

$$\psi_F(x_1,x_2, x_3,...,x_n) = -\psi_F(x_2,x_i,x_3,...,x_n). \quad (2)$$

The Pauli Exclusion Principle is therefore automatically built into the antisymmetric fermionic wave function, thereby forbidding a pair of identical fermions to occupy the same quantum state. This follows because, for $x_1 = x_2$, the wave function in Eq. (2) would equal its negative value, and would therefore vanish. It can be shown from fundamental principles that all bosons have integer values of spin angular momentum, while fermions have half integral spin values. In a subsequent section we will describe several ways to determine spins of elementary particles. Prom such studies, it has been learned that the photon and all mesons are bosons, whereas the leptons and all baryons are fermions. Also, as we have already indicated, every known particle has a corresponding antiparticle. The antiparticle has the same mass as the particle, but otherwise opposite quantum numbers. Thus, the positron (e^+) is the antiparticle of the electron, and carries a negative lepton number and a positive charge. The antiproton (p) has one unit of negative charge and one unit of negative baryon number, in contrast to the proton which is positively charged and has a positive baryon or nucleon number. Certain particles cannot be distinguished from their own antiparticles. For example, the π°, which has no electric charge, is its own antiparticle. It is clear that for a particle to be its own antiparticle, it must, at the very least, be electrically neutral. However, not all electrically neutral particles are their own antiparticles. The neutron has no electric charge, yet the antineutron is distinct because of its negative baryon number and the opposite sign of its magnetic moment. Similarly, the K° meson, although charge neutral, has a distinct antiparticle.

INTRINSIC QUANTUM NUMBERS IN CONNECTION WITH ELEMENTARY PARTICLES:

The elementary particle decay and reactions not only satisfy the conservation laws of charge, mass-energy, momentum and spin but also some other conservation laws. The laws pertain to some intrinsic quantum numbers which are assigned to particles. These are Charge quantum number, Lepton number, Baryon number, Multiplet number, Iso-spin quantum number, hyper charge, strangeness quantum number. However, we will discuss here very few of them as.

i) Charge quantum number q: In elementary particle decay, charge is not only conserved but it is also quantized in units of electric charge e. conservation of quantized charge can be expressed by assigning a charge quantum number q = charge/e to every particle. The charge quantum number for electron is (-1), positron (+1), proton (+1), anti-proton (-1) neutron (0), photon (0) and so on.

ii) Lepton Number L: The electron, the muon, the two types of neutrinos (v_e and v_μ) and their anti-particles are classified as leptons. The group of particles e^-, v_e and their anti-particles e^+ and $\overline{v_e}$ are called e-leptons and are assigned lepton number $L_e = +1$ for (e^- and v_e) and $L_e = -1$ for (e^+ and $\overline{v_e}$). Similarly, the group of particles μ^- and v_μ and their anti-particles μ+ and $\overline{v_\mu}$ are called μ-leptons and are assigned lepton numbers $L_\mu = +1$ for (μ^- and v_μ) and $L_\mu = -1$ for (μ+ and $\overline{v_\mu}$). The lepton number of all other particles, photons and hadrons is zero.

iii) Baryon Number B: The baryon group includes the nucleons and hyperons and their anti-particles. A baryon number B = 1 is assigned to baryons and a baryon number B = -1 to their anti-particles thus B = +1 for baryons (p, n, Λ^o, Σ^+, Σ^o, Σ^-, Ξ^o, Ξ^- and Ω^-) ; B = -1 for their anti-baryons and B= 0 for all other particles i,e photons, leptons and mesons.

iv) Strangeness quantum number S: the quantum number called strangeness was introduced to explain the strange behavior of K-mesons and Λ, Σ, Ξ, and Ω hyperons always produced in pairs, a phenomenon called associated production. They are produced y strong interaction in high energy nucleon-nucleon collisions but decay only very reluctantly by means of weak interaction and have a life time very much greater than 10^{-23} sec showing that they do not decay by strong interaction which they are expected to.

The strangeness quantum number S is defined as the difference of the hyperchargeY and Baryon number B. Therefore, S = Y-B or Y = S+B

i,e the hypercharge Y is the sum of Baryon number B and strangeness quantum number S. Hence

$$q = I_3 + \bar{q} = I_3 + \frac{Y}{2} = I_3 + \frac{1}{2}(S + B)$$

With this relation the strangeness of a particle will be an integer and the strangeness of an anti-particle will have the opposite sign to its associated particle. The strangeness quantum number is zero for the particles which are not strange.

QUARKS

The proton (p) and neutron (n) are essentially two different states of the same particle. In 1963 Gell-Mann and independently George Zweig discovered that hadrons (mesons and baryons) have and underlying order or symmetry called SU(3)- an abbreviation for *special unitary group* of 3x3 matrices. They proposed that all hadrons are composed of three still more fundamental particles which form an SU(3) triplet. Gell-Mann called these particles quarks, and their antiparticles as anti-quarks.

BASIC ASSUMPTIONS: Quarks are brought to be elementary in the same sense as leptons- essentially point particles with no internal structure, but unlike anything else in nature are supposed to have fractional charges. These are also assigned some properties which are whimsically labeled as flavor, charm and colour.

PROPERTIES: The original three quarks were labelled u (for up) d (for down) and s (for strange) and corresponding antiquarks were labelled $\bar{u}$, $\bar{d}$ and $\bar{s}$ respectively. All quarks are supposed to have even parity and spin ½ i,e these are fermions and obey Fermi-Dirac statistics. The charge number q, (in multiples of electronic charge e), Baryon number and strangeness S of the three quarks and their anti-quarks is given below;

Quark	**q**	**B**	**S**	**Anti-quark**	**q**	**B**	**S**
u	+2/3	1/3	0	$\bar{u}$	-2/3	-1/3	0
d	-1/3	1/3	0	$\bar{d}$	+1/3	-1/3	0
S	-1/3	1/3	-1	$\bar{s}$	+1/3	-1/3	+1

It is seen that the magnitude of each of the quantum numbers (q, B, S) for anti- quarks has the same value as those for quarks but with opposite sign.

COLOURED QUARKS

The quark model had some serious problems. It was the presence of two or three quarks of the same type in a particular particle. For example a proton with 2u quarks, a neutron with 2d quarks and their antiparticles with 2 $\bar{u}$-anti-quarks and $2\bar{d}$- anti quarks respectively violated Pauli's exclusion principle which must be obeyed by quarks as these are spin ½ fermions. Similarly Ω^- hyperon is supposed to contain 3s-quarks.

To resolve this difficulty it was suggested that quarks and anti-quarks have an additional property designated as 'Colour' which had three possibilities called *red*, *green* and *blue* for quarks and *anti-red*, *anti-green* and *anti-blue* for anti-quarks. According to colour hypothesis all the three quarks in a Baryon have different colours which satisfies Pauli's exclusion principle since all of them are in different states even if two or three of them are otherwise identical. Such a combination can be considered to be white or colourless by analogy with the way in which red, green and blue light combine to make white light.

Again according to colour hypothesis a meson is supposed to consist of a quark of one colour and an anti-quark of corresponding anti-colour thus cancelling the colour effect as it is supposed that a colour and its anti-colour combine to form white. The Ω^- hyperon consists of three quarks S_R, S_B, and S_G i,e 3s-quarks of different colour states Red, Blue and Green. Thus we find that both Baryons and mesons are always colour less. The quark colour is a property which has significance only within the hadrons but is never directly observable.

Importance: Since hadrons seem to be composed of quarks, the strong interaction between hadrons should ultimately be traceable to an interaction between quarks. The force between quark works on the line of an exchange force. The particles that quarks exchange are called gluons. Gluons are massless, spin 1 particles travelling at the speed of light and each one carries a colour and an anti colour. The gluons must therefore, be represented as combination of a colour and a different anti-colour. Gluons are said to be eight in number.

CHARMED QUARK (C)

By analogy with four leptons (e-neutrino, μ-neutrino, electron and muon) a new (fourth) quark was proposed to supplement the original u, d and s trio. The quark was named 'charmed' or (c) quark. The c quark has charge number q =+2/3, strangeness S =0 and charm quantum number +1. Other three quarks have zero charm. The anti charm ($\bar{c}$) quark has a charge number q = -2/3, charm quantum number -1 and strangeness S = 0.

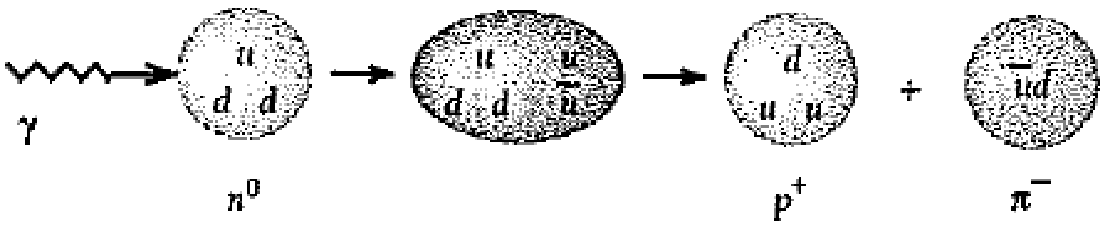
Charm is supposed to influence the likelihood of certain hadrons decays. A recently discovered heavy meson is believed to consists of a charmed quark and an anti-charmed quark i,e its quark construction is (c $\bar{c}$).

QUARK CONFINEMENT

But for all the persuasiveness of the quark model of hadrons, and for all the searching that has gone on since 1963, no quark has ever been isolated. The present status of quarks may seem like that of neutrinos for twenty five years after they were proposed: their reality is suggested by a wealth of indirect evidence, but something in their basic character impedes their detection. The parallel is not really accurate. However, the elusiveness of the neutrino was due merely to its feeble interaction with matter. On the other hand, the fundamental aspect of the color force seems to prevent quarks from existing independently outside hadrons. Indeed, the detection of a free quark would represent a failure of the theory, called quantum chromo-dynamics, that describes them and their behavior.

The explanation for quark confinement begins with the idea that, as though they were connected by a spring, the attractive force between two quarks goes up as the quarks move apart from their normal spacing. This means that more and more energy is needed to increase their separation. But with enough energy added, instead of a quark breaking free from the other in a hadron, the excess energy goes into producing a quark-antiquark pair. This results in a meson that does escape. To illustrate the effect, figure below shows what happens when an energetic an energetic gamma-ray photon impinges on a neutron (composition ud$\bar{\text{d}}$) and causes a u$\bar{u}$ quark-antiquark pair to come into being. The quarks udd + u$\bar{u}$ then rearrange themselves into a proton (duu) and a negative pin ($\bar{u}$d), so that the net reaction is

$$\gamma + n^0 \rightarrow p^+ + \pi^-$$



Quark confinement is not the only example in physics of things that cannot be separated- the north and south poles of a magnetic cannot be freed from each other either. If we pull apart a magnet so that it breaks we then have two magnets, each having a north and a south pole, instead of independent north and south poles.