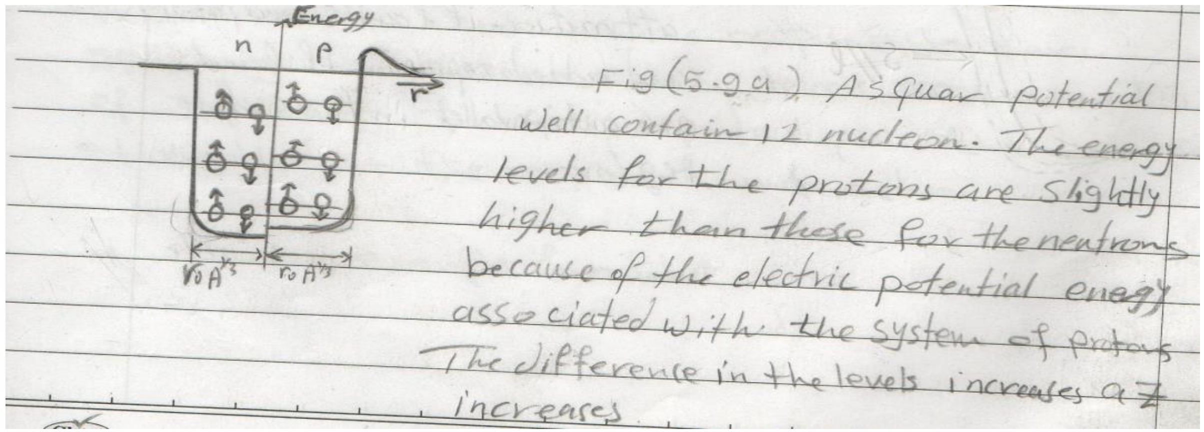
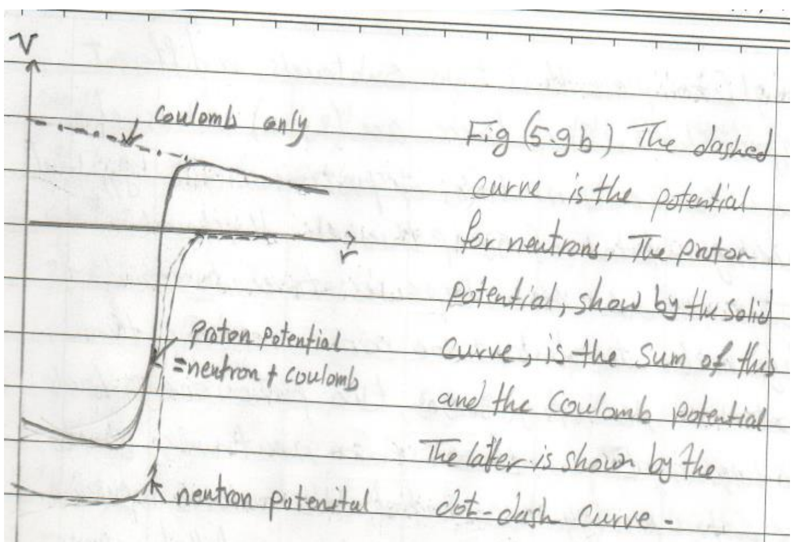
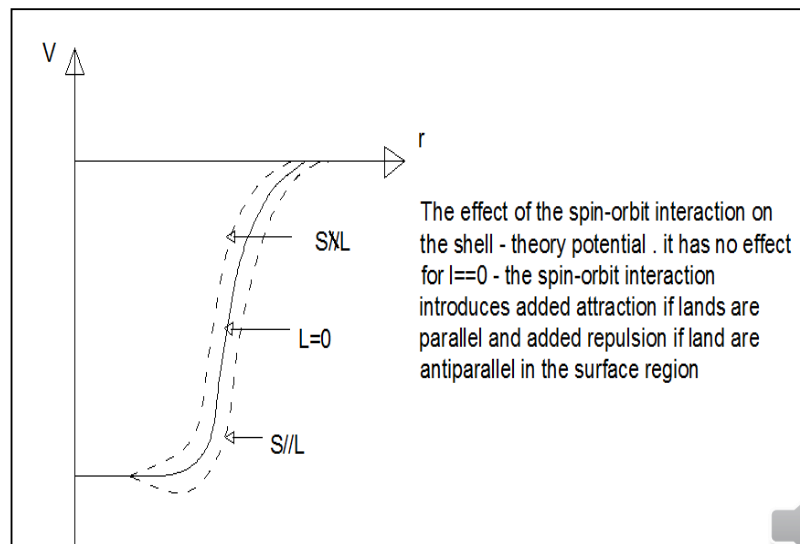
المحاضرةالخامسة تكملة الفصل الخامس + الفصل السادس(Nuclear Reaction)

أ.د الطاف عبد المجيد سلمان

As Z increases and higher states are filled, a proton level for a given quantum No. will be much higher in energy the neutron level for the same quantum No., it will be even higher in energy than neutron levels for higher quantum No. As a results, it is more energetically favorable for the nucleus to form with neutron in the lower energy levels rather than proton in the higher energy levels so that the No. of neutron is greater than the No. of proton.







The Shell Model:- The IPM was quite successful in explaining many important feature of nuclei such as the occurrence of magic Nos. which provide the stability of nuclei and the ground state properties of odd A nuclei. Its major short- coming was the degeneracy of the ground states for even-A nuclei, besides disagreement with other experimental properties. The reason for this degeneracy is because of its assumption that the average potential exhaust the entire nucleon-nucleon interaction.

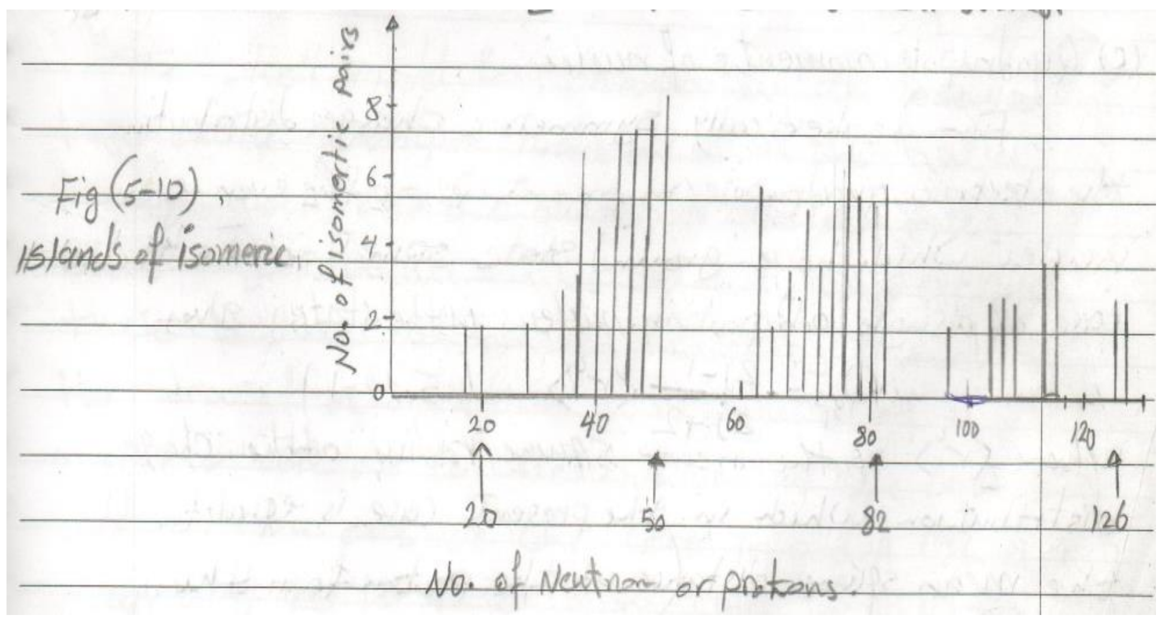
Therefore in the shell-model, which is an extension of the IPM, this assumption is modified as "though a major part of the nucleon interaction is used up in giving rise to an average potential, these is still some residual nucleon-nucleon interaction left. This residual interaction is weak and is responsible for splitting the two nucleon level. The amount of splitting of levels depends upon the strength of the residual interaction.

H.W. Give Example For That .

5.10 Application of Extreme Single Shell Model

(a) Nuclear Spin:- An even No. of nucleon of any one kind in the same j always combines to give the resultant spin (0) and even parity. The total angular momentum of any shell with an even No. of nucleon is zero, while the angular momentum of any shell will an odd No. of nucleons is equal to the angular momentum of the last odd unpaired nucleon. Further, it is assumed that the neutron and proton states fill independently, so that the state in which a proton goes is independent of the No. of neutrons in the nucleus and vice-versa. The above assumption constitue the basis of what is known as the extreme single particle shell model. In the case of ^3H with (N=2, Z=1), the single proton should occupy the (1S) level with (j=1/2, l=0 so I=1/2 and its parity is even), so that the ground state of ^3H is $(1/2)^+$ similarly in the case of ^3He with (Z=2, N=1), so that its ground state is also $(1/2)^+$ [in a self-consistent spherically symmetric potential, the levels have definite parity which is determined by (l) values, for l=0 and even, parity is even (+), for (l) odd, the parity is odd (-)].

(b) Islands of Isomerism:- Relatively long lived nuclear excited states, known as isomeric states in some nuclei. These occur when there is a large difference in angular momenta between the excited and ground states, specially when the energy difference between the two states is relatively small. Isomeric states are mostly found amongst nuclei for which either N or Z is near the end of a shell. These regions are known as islands of isomerism Fig. (5-10). The grouping of the nuclei with isomeric states is most prominent just below the major closed shells at Z or N equal to 50 and 82. The grouping is less marked near=126.



Consider the nucleus ^{115}In with (Z=49 and N=66). Its ground state spin and parity are $9/2^+$ showing that the last odd unpaired proton occupies the $1g_{9/2}$ sublevel while the rest of the protons fill up all the lower sublevels up to $2P_{1/2}$ in pairs. When excited, one proton from $2P_{1/2}$ is raised to the $1g_{9/2}$ sublevel to form a pair with the odd proton in the latter leaving an unpaired nucleon in the $2P_{1/2}$ sublevel. The excited state has spin-parity ($1/2^-$). Its energy is relatively low, being only 335 KeV. The transition from this state to the ground state is M4 since it involves a spin charge $\Delta I=4$ with change of parity. This is in agreement with the experimental results. The life time of the excited state is 14.4 h.

(c) Quadrupole moments of nuclei:- For a spherically symmetric charge distribution the electric quadrupole moment (Q =0) for even-even nuclei which have ground state spin (I=0). In the case of a single odd proton nucleus in the state j gives $Q_{SP}= - [2j-1/2j+2]*<r^2>$ --- (5.10.1)

Where $<r^2>$ is the mean square radius of the charge distribution which in the present case is equal to the mean squar distance of the proton from the nuclear centre. The negative sign on the r.h.s. of (5.10.1) show that orbital motion of the proton in the equatorial plan makes the change distribution an oblate spheroid for which ($Q<0$). On the other hand an odd hole in the state j would make the charge distribution a prolate spheroid for which ($Q>0$). In the case of a single odd neutron a small Q_{Sn} may be expected $Q_{Sn} = (Z/A^2)* Q_{SP}$ --- (5.10.2)

This is much smaller than Q_{SP}. The measured values of Q for odd A nuclei are in many cases much higher than the estimates given above. The single particle shell model cannot explain the very large values of Q in many nuclei.

5.11 Collective model

The shell model fails in explaining the observed large electric quadrupole moments Q of the nuclei in many cases and the quadrupole transition rates $B(E_2)$. J. Rainwater was the first who explain these failures of the shell model by introducing the idea of deformation in the shape of the nuclear core due to the motion of the loss odd nucleon outside the core in odd A nuclei. According to him such motion leads to a polarization of even-even core, which assumes a spheroid shape. Such deformation would cause the quadrupole moment to be higher than the single particle value. E_2 transition rate is also increased. Aage Bhor and B. Mottleson further elaborated the model, combining the single particle and collective motions into a unified model which gave a more complete description of the deformed nuclei. In nearly spherical nuclei, the coupling between the collective motion of the nucleons in the core and the motion of the loose particles is not spherically symmetric. These particles moving in a non-spherically symmetric shell model potential, maintains the deformed nuclear shape. We can write the total energies of the nucleus as $E_{tot} = E_{rot} + E_{vib} + E_{nuc}$. The collective motion of the nuclear core gives rise to the rotational and vibrational term, while nucleonic energy term is due to the motion of the loose nucleons. The coupling of the external nucleonic motion and collective motion gives rise to shape-oscillations.

Experimental evidence shows that far from the closed shells, the motion of the loose nucleons produces large permanent deformations, characterized by rotational spectra. The nuclei are found in middle of 1d, 2S shells in the range $145<A<185$ and for $A>226$. The energy difference between the 0^+ ground state and the 2^+ first excited state is of the order of 100 KeV in them. Far from the deformed regions and nearer the closed shells, the equilibrium shape is spherical. Low energy excitations produce characteristic vibrational spectra. At the closed shells, excited states can be produced by the breakup of the core, giving rise to new particle states.

Chapter Six
Nuclear Reaction

6.1 Nuclear Reaction

When the very high velocity α particle made head-on collisions with the nitrogen nuclei ^{14}N some of them were captured by the latter. The composite system, which was formed as a result of such capture, almost immediately (within~ 10^{-15} S) disintegrated by the emission of a proton of very high velocity. This was the process of nuclear transmutation brought about artificially with the help of α particle from a radioactive substance, leaving a residual nucleus of the isotope ^{17}O of oxygen

$^{4}_{2}He + ^{14}_{7}N \longrightarrow ^{18}_{9}F^{*} \longrightarrow ^{17}_{8}O + ^{1}_{1}H$ --- (6.1.1)

the intermediate step ^{18}F is known as a compound nucleus. It breaks up almost immediately after its formation.

A nuclear reaction refers to a process which occurs when a nuclear particle (nucleon, a nucleus or an elementary particle) comes into close contact with another during which energy and momentum exchanges take place. The final products of the reaction are again some nuclear particle or particles which leave the point of contact in different directions. The changes produced in a nuclear reaction usually involve strong nuclear force. A nuclear reaction can be represented by $^{A}_{Z}X + x \longrightarrow ^{A'}_{Z'}Y + y$ --- (6.1.2)

Or simply as $^{A}X\ (x,y)\ ^{A'}Y$

Nucleus breaks up almost immediately by ejecting a particle y, leaving a residual nucleus Y. the projectile x and the emitted particle y are in many cases light nuclei such as proton (P), Neutrons (n), Deuterons (d), α particles, $^{\gamma}$- rays etc.

6.2 Types of nuclear reactions

The artificial transmutation of a nucleus produced in the pioneering experiment of Rutherford is a type of nuclear reaction various types of nuclear reactions have since been produced. These can be classified as

(a)Elastic Scattering: in this case the ejected y is the same as the projectile x. it comes out with the same energy and angular momentum as x, so that the residual nucleus Y is the same as the target X and is left in the same state (ground state). We can represent the process as X (x, x) X.

(b) Inelastic scattering: in this case y is the same as x. but it has different energy and angular momentum, so that the residual nucleus Y(=X) is left in an excited state. The process can be written as X (x, y) X^*.

(c) Radiative capture: in this case the projectile x is absorbed by the target nucleus X to form the excited compound nucleus, which subsequently goes down to the ground state by the emission of one or more $^{\gamma}$- ray quanta X (x, y) Y^* .

(d) Disintegration process: we can represent the process as X (x, y) Y where X, x, Y and y are all different either in Z or in A or in both. The first nuclear transmutation observed by Ratherford is an example of this process ^{14}N (α, P) ^{17}O.

(e) Many body reaction: when the K.E. of the incident particle is high, two or more particles can come out of the compound nucleus if y_1, y_2, y_3 etc, represent these different particles. We can write the reaction Eq. as X (x, y_1, y_2, y_3, --) Y. examples are ^{16}O (P, 2P) ^{15}N, ^{16}O (P, Pn) ^{15}O, ^{16}O (P, 3P) ^{14}C etc. when the energy of x is very high, a very large No. of reaction products usually result. Such reactions are known as spallation reactions.

(f) Photo-disintegration: in this case the target nucleus is bombarded with very high energy $^{\gamma}$- rays, so that it is raised to an excited state by the absorption of the latter. The compound nucleus ($C^* = X^*$). The reaction can be written as X ($^{\gamma}$, y) Y.
(g) Nuclear fission: when X is a heavy nucleus and y, Y have comparable masses, the reaction is known as nuclear fission.
(h) Elementary particle reactions: these involve either the production of elementary particles other than nucleons or nuclei as a result of the reaction or their use as projectiles or both of these. Example are:
(I) $P + P \rightarrow P + n + \pi^+$, (II) $\pi^- + P \rightarrow \pi^0 + n$, (III) $P + \pi^0 \rightarrow K^0 + \Lambda^0$ etc
These reactions are usually produced at extremely high energies which may be several hundred MeV or more.
(i) Heavy ion reactions: in these reactions the target nucleus is bombarded by projectiles heavier than α particles. Various types of products may be produced. The reactions usually take place at fairly high energies (several hundred MeV) of the projectile example are: (I) ^{10}B (^{16}O, ^{4}He) ^{22}Na, (II) ^{14}N (^{14}N, ^{15}N) ^{13}N etc.

6.3 Conservation Laws in Nuclear Reactions

The occurrence of a nuclear reaction is usually governed by certain conservation laws
(a) Conservation of mass number: the total No. of n and P in the nuclei taking part in a nucleon reaction remains unchanged after the reaction. The reaction X (x, y) Y represented by Eq. (6.1.2). The sum of mass No. of X and x must be equal to the sum of the mass No. of Y and y $A + a = A^- + a^-$ (6.3.1)
(b) Conservation of atomic number: the total No. of protons of the nuclei taking part in a nucleon reaction remains unchanged after the reaction $Z + z = Z^- + z^-$ --- (6.3.2)
in view of (a) and (b) the neutron No. (n) remains unchanged in the reaction.

(c) Conservation of energy: (Q value of a nuclear reaction) conservation of energy requires that the total energy, including the rest mass energies of all the nuclei taking part in a reaction and their kinetic energies, must be equal to the sum of the rest mass energies ant the K.E. of the products,

$M_X C^2 + M_x C^2 + E_X + E_x = M_Y C^2 + M_y C^2 + E_Y + E_y$

during the nuclear reaction, the target nucleus is usually at rest, so that ($E_X = 0$) the above Eq. become

$M_X C^2 + M_x C^2 + E_x = M_Y C^2 + M_y C^2 + E_Y + E_y$ --- (6.3.3)

(d) Conservation of linear momentum: the law of Conservation of linear momentum in an arbitrary frame of reference gives $P_X + P_x = P_Y + P_y$ --- (6.3.4)

In the laboratory frame of reference (L-system) in which the target nucleus is at rest (P_X=0) and the above Eq. becomes $P_x = P_Y = P_y$ --- (6.3.5) In the frame of reference in which the centre of mass of the two particles before collision is at rest (c-system), we have to write ($P_X + P_x$= 0), which gives ($P_Y + P_y$ = 0), the centre of mass on the products is also at rest in this system.

(e) Conservation of angular momentum: the total angular momentum of the nuclei taking part in the reaction remains the same before and after the reaction. Let i_X, i_x, i_Y, i_y, denoted the total angular momentum of the nuclei X, x, Y and y respectively. Let (l_X) represent the relative orbital angular momentum of X and x (initial state), similarly (l_Y) denoted the relative orbital angular momentum of Y and y (finial state). Then according to the law of conservation of angular momentum $i_X + i_x + l_X = i_Y + i_y + l_Y$ --- (6.3.6)

(f) Conservation of parity: the parity π_i before the reaction must be equal to the parity π_f after the reaction. The conservation of the parity for the initial and final states of the reaction $\pi_X . \pi_x (-1)^{l_X} = \pi_Y . \pi_y (-1)^{l_Y}$ -- (6.3.7)

(g) Conservation of isotopic spin: from the law of conservation of isotopic spin applicable in the case of strong interaction $T_i = T_f$, since for the reaction X + x—› Y + y, $T_i = T_X + T_x$ and $T_f = T_Y + T_y$, we have

$T_X + T_x = T_Y + T_y$ ---(6.3.8)

Isotopic spin is a characteristic of the nuclear level. The above conservation law can be used to identify the levels of the nuclei produced in the reaction. In particular if ($T_x = T_y$ = 0) as for the deuteron or the α particle, we must have $T_X = T_Y$. This rule must be obeyed in reactions of the type (d, α), (d, d), (α, d), (α, α) etc. the rule has been verified for the nuclei $^{6}Li_3$, $^{10}B_5$ and $^{14}N_7$ for (T=0) in the ground states.

6.4 Collision Between Subatomic Particles

In the experimental arrangement, a beam of mono-energetic particles, called projectiles, is allowed to fall on the target containing the nuclei which are at rest. The collision between a projectile and a target nucleus can be analyzed from the point of view of an observer at rest in the laboratory. This is known as the laboratory frame of reference or the L- system. Alternatively, the collision may be analyzed from the point of view of an observer at rest with respect to the center of mass of the colliding particles, known as the C-system.