CHAPTER I

INTRODUCTION

1.1 DISCOVERY AND SHORT SURVEY OF NUCLEAR FISSION :

The discovery of 'nuclear fission' is the unexpected result of the 'hunt' for transuranic elements that follow uranium in the periodic table. The starting point is to be traced back to the attempt of Fermi[1] and his co-workers in 1934, to produce elements of atomic number greater than 92 by bombarding uranium with neutrons. In their early experiments they found four beta ray activities with different half lives (T_1 = 10 s, T_2 = 40 s, T_3 = 13 m, T_4 = 90 m). Since normal uranium decays by Alpha particle emission with a long half life, the above activities indicated formation of new elements, probably elements of atomic number greater than 92. From the chemical tests it was confirmed that these beta-activities could not be attributed to any of the elements in the range of atomic number 86 to 92 inclusive. It was, therefore, concluded by Fermi that the elements 93 had been produced. This element was assumed to be produced by beta-decay of uranium upon the capture of a neutron. However, Fermi's conclusion began to seem doubtful, because in the opinion of different workers the chemical manipulation he had performed allowed for another interpretation also. This provoked a tremendous interest among different workers, particularly I. Curie[2] and her co-workers, Hahn and strassmann[3] and Meitner[4] who entered this field in search of the transuranic elements. Uranium, thorium and protoactinium were bombarded with neutrons and many different beta-ray activities were discovered.

In 1938, Hahn and Strassmann[3] directed their attention to a 3.5 hour half life substance, detected by Curie and Savitch[5] as a product of irradiation of uranium by slow neutrons. After careful chemical analysis they observed barium and krypton as product of the reaction. Thus they proposed a new hypothesis that uranium after capturing a neutron might break up into two large fragments of comparable masses barium (z = 54) and krypton (z = 36).

Meitner and Frish[4] were first to give the physical explanation of the process. They suggested a name fission, borrowed from the biologist~~s~~ W.A.Arnold. The theory of the process was given first by Bohr and Wheeler[6]. They pictured a gradual deformation of the excited nucleus, in which it is elongated, formed a waist and finally separated into two nearly equal parts. They estimated about 100 MeV of kinetic energy per fission product.

The type of fission in which a projectile is required to break up the target nucleus is known as induced fission. It was also reported that heavy nuclides with mass number of 230 or more exhibits this fission phenomenon sponteneously without any projectile as in the previous case. This was termed as sponteneous fission. Since then this phenomenon has been studied extensively by large number of workers[7-16] throughout the globe. Gamma rays, x-rays, high-speed electron, proton, deuterons and alpha particles have been used as projectiles to induce fission in uranium, thorium and other heavy nuclei.

The experimental investigation have been made to collect informations regarding (1) energy release, (2) charge and mass distribution of fission products, (3) angular correlation between the fission fragments, (4) emission of other particles in the process. All these experiments mainly aimed at, were in search of a nuclear model which can explain fission phenomenon properly. However, excepting certain order here and there no model is yet available to account for the fission phenomenon completely.

At present heavy ion fission[17], fission by bremsstrahlung[18] and tunnelling[19] have been a field of wide interest and importance. Apart from usual binary break up the study of ternary fission and quaternary fission creates a keen interest amongst the workers in the field.

1.2 FISSION MECHANISM :

The theoretical explanation of the nuclear fission is one of the most interesting and difficult problems of Nuclear Physics. Since the process is accompanied by the strongest deviations of the shape and the internal structure of the nucleus from their equilibrium values compared to with any other nuclear processes. The phenomenon occuring in different stages of fission are very greatly varied in their physical nature, and it is difficult to construct aunified theory describing the entire fission process.

To explain experimental data, one uses therefore different model describing nuclear fission process.

Liquid drop model : The liquid drop model of the nucleus as conceived by Bohr[20] and Kalckar[21] argues nucleus to be an incompressable charged drop of liquid. The nucleons are allowed to move collectively and thought to have strong interaction on each other. The nuclear levels are represented as quantised states of the nuclear system as a whole and not as a state of single particle in an average field. One important aspect of this model is that the nuclear field possesses a high surface tension, the surface energy per single nuclear particle is 5 MeV of energy. This actually predicts the energy that would be required to remove a nucleon from nuclear surface against the 'cohesive surface tension' and that is analogous to heat of evaporation per molecule for ordinary liquid drop. If extra energy is added by the absorption of an outside neutron or other charged particles, used as projectile, the spherical nucleus may be distorted into a Dumb-bell shape and then break at the neck into two nearly equal fragments releasing enoromous energy. In the break up process the liquid drop passes through a series of stages[22] as shown in Fig. 1.1.

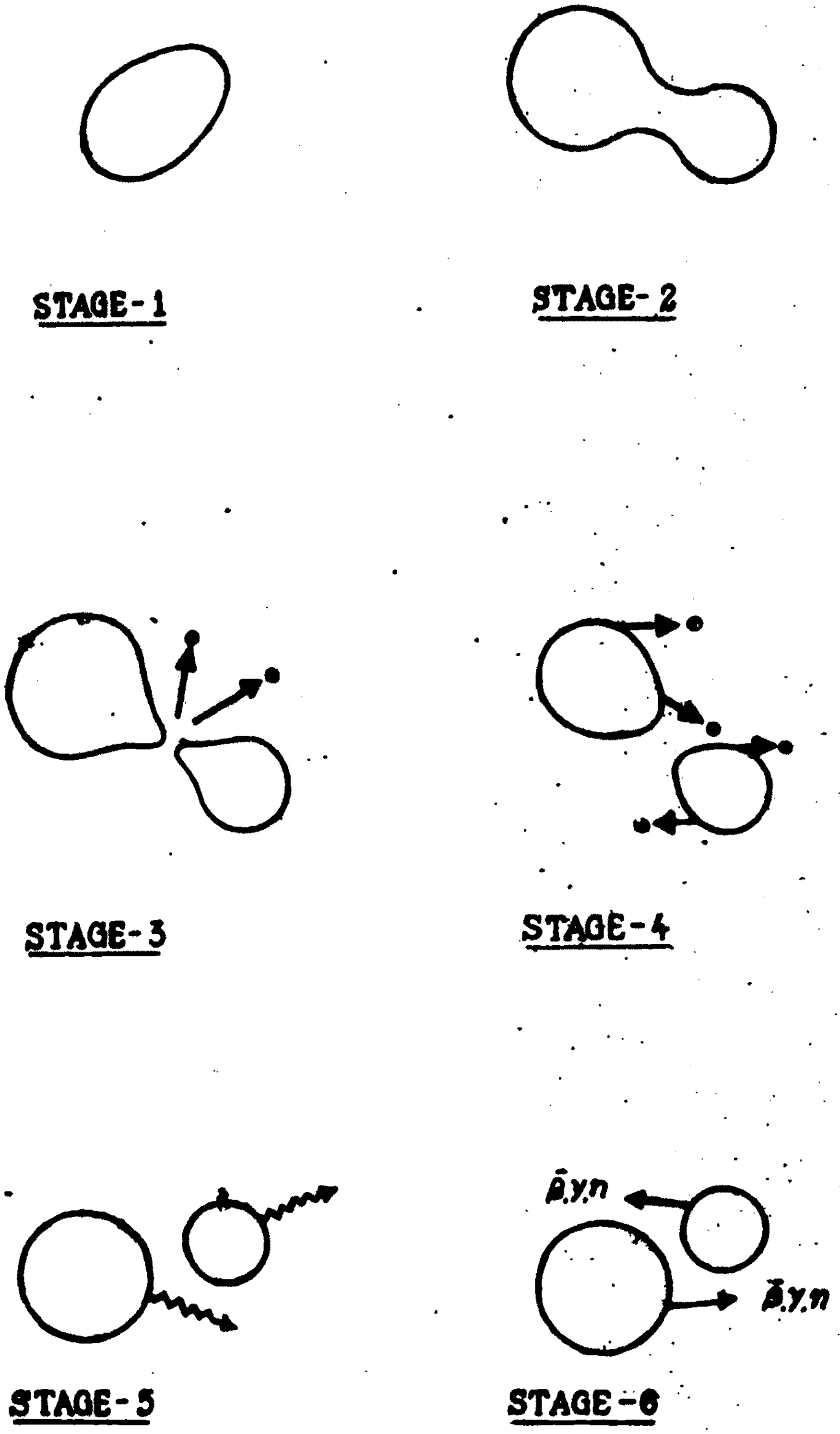

Fig 1.1 DIFFERENT STAGES OF AN EXCITED NUCLEUS LEADING TO BINARY FISSION

The stage 1, is the excitation of the nucleus by the absorption of a charged particle or a neutron from the out side of the atom. The excess energy added to the nucleus causes it to undergo rapid changes of shape, oscillating from one form to other until finally it assumes the elongated shape called the transition state nucleus. The second stage represents the saddle point which is the critical part of the fission process. Here the attractive nuclear forces between the nucleons are momentarily in balance with the repulsive electrostatic forces between the positively charged protons. The nucleus, if contracts slightly, will return to its oscillations and excess energy will be released in the form of electromagnetic radiation of high energy. On the other hand if it stretches a little more, the internal disruptive forces (arising out of coulombian repulsion) gain control of the affair and nucleus attains a stage of no return and it is committed to fission. At the third stage (the fission point), the nucleus will finally break into two large pieces, called the fission fragments and it may emit several neutrons at this stage. Both the fission fragments are positively charged and they have mutual electro-static repulsion and due to which they fly apart in opposite direction in much the same way as the like poles of two magnets repel each other. The fragments will have large excess of internal excitation energy (analogous to heat energy) besides their kinetic energy due to their motion, most of which they will lose first by boiling of neutrons that actually happens in stage 4. In stage 5, gamma rays are found to be emitted. Both the neutrons and gamma rays emitted at this stage are called prompt to differentiate these emanations from those delayed one that occur at a later stage. The process from the original excitation of the nucleus to the emission of gamma rays will take about 10^{-11} second. These fragments as fission products now come to rest and becomes radio-active elements (stage 6). The fission fragments then begin to emit gamma rays, x-rays and beta-rays consisting of negatively charged electrons that are produced when neutrons furn into protons and some times a delayed neutron over a period of time that may range from few seconds to many years, until they have no more excess energy left to disintegrate further and turn into a ordinary stable isotopes.

Fissionability in the case of idealised nucleus can be expressed in terms of parameter 'X' introduced by Bohr and Wheeler[6]. 'X' can be defined as 1/2 (Electrostatic energy for charged sphere / surface energy of sphere). The electrostatic energy is proportional to $z^2/A^{1/3}$ whereas the surface energy depends on A. Thus 'X' is proportional to z^2/A. Nuclei with $(z^2/A)_{cri} > 50.13$ can not exist, because instability increases with respect to arbitrary small distortion and it will elongate more and more until it breaks up. On the other hand, for nuclei with less than the critical value of z^2/A, a finite distortion is required to overcome the surface tension and the amount of excess energy needed increases as the value of the ratio z^2/A decreases.

Although the description of fission with the framework of the liquid drop model has made it possible to understand the main feature of the fission process, but many experimental results obtained in the low energy fission of nuclei remained unexplained. One of them being asymmetry in the distribution of mass of the fragments of the fissioning nucleus. However, a number of methods reconcilling the asymmetric mass distribution in fission within the perview of liquid drop model has been suggested in which the properties of nuclear fluid such as inhomogeneity, the inertia, the compressibility and polarizibility are taken into consideration. Fission asymmetry is also related to the excitation energy of the nuclei. The lower the excitation energy of the nuclei before fission the greater will be their contribution towards asymmetric break up. The nuclei that have 'shed' neutrons will fission in cooler state and therefore more anisotropically than nuclei that have experienced no preliminary neutron sheding. Thus Barnanov[23] et al pointed out that nuclei that have shed neutrons before fission undergo more asymmetric and anisotropic fission than nuclei that have not first shed neutrons. Again at the same time it has been established experimentally that with increasing nuclear excitation energies of 50 to 60 MeV the structure factor weakens[24] and disappear almost completely. S. A. Karamayan[25] et al observed in heavy ion fission of Bismuth and Uranium, that at high excitation energy of the fissioning nucleus the mass and charge distribution can be considered in the frame work of statistical description of the excited nucleus. The most systematic study has been made of the behaviour of the fragment mass distribution as function of the excitation energy for a comparatively lighter nuclei for which $X = (z^2/A)/(z^2/A)_{cri} < 0.7$. The data obtained by Plasil[26] agree well with the theoretical calculation of Nix and Swiatecki[27], but this calculation is not applicable with region $X > 0.7$ and the experimental data for this case are scarce. Nix[28] theory predicts that at moderate excitation energy, mass distribution from the fission of lighter nuclei to be broader than those from the fission of heavier nuclei whereas the total K.E. distribution for the lighter nuclei are predicted narrower than for the heavier fission nuclei. In sponteneous and slow neutron fission, the symmetric fission is sub-barrier[29] and the yield of symmetric fragments calculated using barrier-penetration formula[30] for sponteneous fission is too low compared to the measured symmetric fragments yield. This probably indicates that the asymmetric fragments were formed by a passage of the fissioning nucleus through an asymmetric saddle point with subsequent dynamic effects which gives a tendency towards symmetric shape.

The liquid drop model for explaining the fission process, suffers another set-back, when it failed to account for the calculated fission thresh-hold not in accordance with the experimental facts. This leads in turn to the appearance of a number of new models in which the premises of the liquid drop model of the nucleus are used to a greater or lesser degree and the influence of the microscopic structure are taken into account phenomenologically (allowancefor single particle, and collective effects, shell correction, statistical factor). However, the use of liquid drop model for description of fission of excited nuclei is sufficiently well founded. Indeed for the fission of nuclei with $30 \leqslant z^2/A \leqslant 37$, the experimental results connected with fission product yields, the kinetic energy of the fragments etc. agree sufficiently well with calculations based on the liquid drop model. It must be noted that for this region of nuclei in liquid drop fission, the saddle point and scission point practically coincide, and the final results do not depend on the assumptions made concerning the character of the motion of the nucleus from saddle figure to scission figure. A more complicated situation arises when z^2/A increases since the deformation of the saddle figure becomes negligible and the assumptions concerning character of the descent becomes significant for the determination of the probabilities of the yield of the final products. Thus it can be concluded that the liquid drop model describes fission of relatively light nuclei in general terms, but it should not be used in those cases where accurate quantitative predictions are required[31].

Shell-model : The shell model explains the behaviour of a nucleon in the nucleus. It is also known as independent particle model. According to this model, the protons and neutrons are arranged in shells in the nucleus similar to extra nuclear electrons in various orbits outside the nucleus.

It was pointed out by Mayer[32] and also by Meitner[33] that the asymmetry of fission might have some connection with the shell model of the nucleus. If more than 132 neutrons are available, fragments would tend to form closed shells of 50 and 82 neutrons respectively. The fission of bismuth ($z = 83$, $N = 126$) by fast particle is predominantly symmetric, the reason assigned there of, by Meitner[33] is due to the fact that there are not enough neutrons to form two closed shells as mentioned above. It was suggested that the difference lies in the high energy of the particle needed to cause fission of bismuth. However, at this high energy, it is likely that a number of neutrons are evaporated first and that the ultimate fission process occurs with little energy to spare. This is similar to slow neutron fission of uranium. On the other hand, it appears some what complex as to what extent the neutron shell can be assumed to be effective in the highly excited and badly deformed nascent fragments.

The specially stable configuration of 50 and 82 neutrons or protons which are among those postulated for the shell model are expected to influence both binding energy and radii of neclei. Irregularities of binding energy of several MeV are in fact indicated by mass spectrometer measurement, which are however, not yet completely reliable in the region of interest. Variations of energy in the neighbourhood of the shell containing 126 protons and neutrons can be deduced from the alpha-particle energies[34]. These might be sufficient to make asymmetric fission energetically more favourable[35]. However, it is observed that asymmetric mode of fission predominates in the low energy fission as the neutrons and protons tries to form closed shells, contrary to the fission at high energy where symmetric mode predominates, as the closed nucleonic shells form less rapidly[36]. The shell model has also been invoked to explain the delayed neutron emission in fission. Glendenin[37] has suggested that delayed neutron emitters of this type might be responsible for irregularities in the mass yield curve discovered by Thode and Graham[38]. However, it was only a qualitative explanation of the anomalus fission yields, more quantitative estimation did not fit observed data very well. A-gain in estimating the shape of the fissioning nucleus on the basis of the Bohr Wheeler[6] theory, Frankel and Metropolies[39] observed the absence of neck at which the deformed nucleus might break. The fission process is a slow[40] one and as such surface wave travels from one end to other many times before a definite neck develops and fission occurs. As the scission[41] time is longer than the characteristic nuclear time and nuclear relaxation time, it might be well argued that the fission modes will be determined at a rather late stage, probably just before the separation of the fragments. Further, because of the slowness of the fission process, we may assume that an instantaneous statistical equilibrium will be established at any instant of the process from saddle point to scission point[41a]. According to this assumption, any relative probability of occurance is proportional to the corresponding density of quantum states of the corresponding nuclear configuration at the moment, just before scission when statistical equilibrium is established.

Collective Model : To improve the agreement with experiment, Rainwater[42], A. Bohr[43] and others[44] have explored the possibility of a model, known as Collective Model which combines the features of the independent shell particle model and liquid drop model together. According to this model, it is possible to interprete the sum of the individual energies and interaction energies of a complex system of particles as a surface energy, which comprises a surface vibration energy, a surface rotation energy and a surface potential energy. Changes in the totality of individual particle state, gives rise to different surface energies. It is reasonable to describe the result of the individual particle wave functions as giving rise to a rapidly varying membrane like nucllear surface. The nucleus, when, somewhat disturbed from major closed shell, this surface can undergo oscillation like a conventional liquid drop and can easily be distorted into a non-spherical shape by free nucleons occupying higher stages. This distortion reacts back on the individual particle states, so that the effect of the coupling of such particle to the surface created a strong indirect inter-particle coupling. This indirect inter-particle coupling results in collective permanent states of distortion and consequently in large quadrapole moments[45]. Thus the collective model can be used to describe the drop like properties like nuclear fission, which at the same time preserving shell characteristic. However, in the simple liquid drop model, the energy incident on the nucleus passes through a complicated many stage process of its redistribution before getting concentrated on the mode of deformation that leads to fission. Consequently it would be expected on that, on the impenetrable fluid idealisation that correlation should be practically absent between the direction of incidence of energy and direction of emergence of fission fragments. On the contrary the observation of photo-fission of even nuclei show that the angular distribution of the fragments is of the form,

$$n(\theta) = 1 + A \sin^2\theta.$$

With anisotropy parameter A decreasing fast with energy, thus the distribution show isotropic, a few MeV above thresh hold. The anisotropy increases with mass asymmetry and odd nuclei show no anisotropy. This finds a constant and natural explanation on the collective model of the nucleus proposed by number of workers[43, 44, 46].

Unified model : According to unified model, nuclei are deformed away from a spherical shape because the nucleus is not a rigid structure[47], and nucleons outside the closed shell can set up tension in the closed shell core causing thereby a polarisation of the nucleus. The mechanism by which this done is that a few nucleons outside a closed shell are allowed to orbit a spherically shaped closed shell core. If the forces between the external nucleons and the core are repulsive, there is a tendency to polarise the core by pushing the equatorial plane towards the centre of the nucleus to form a prolate spheroid. On the other hand, if the forces are attractive, polarisation is accomplished by pulling out the equatorial plane to form an oblate spheroid. The resulting deformation is observed experimentally as a quadrupole moment, and the larger the amount of deformation, the larger the magnitude of the moment.

We know very much about the atomic nucleus, but unfortunately, no single model has been found that can correlate all or even a major fraction of the existing experimental data. The particular marriage of the independent particle and liquid drop models gave birth to collective model and unified model and the whole of the family can be made to explain the outstanding nuclear problem like fission, as and when we require.

1.3 SECONDARY EMISSION :

A great number of particles are supposed to be emitted during or after the fission process. The prominant amongst them being neutron both delayed and prompt, the alpha particles and gamma rays. A close watch on their emission probability, the energy distribution and angular distribution may give informations about the fission process in its various stages, as these emissions are not simulteneous.

The great majority of the neutrons produced in fission are released within about 10^{-14} sec and are known as prompt neutrons. A small proportion of neutrons are emitted for some times after the fission process is taken place. They are named as delayed neutron. A comprehensive summary of the large amount of informations available on prompt neutrons have recently been given by Torrel[48]. The strong directional correlation of the evaporated prompt neutrons with the fragments immediately suggests that such neutrons may be useful for studying the division of excitation energy between the fragments, especially since 2.5 to 3.5 prompt neutrons per fission carry of 16 to 24 MeV or about two- thirds of the prompt excitation energy of the fragments. Frasher and Milton[49] who made the surprising discovery that in the symmetric mass region lighter fragments emits more neutrons than heavy ones. It is also been observed by Baranov[23] that the nuclei that have shed neutron will fission in cooler state and therefore anisotropically than nuclei that have experienced no preliminary neutron sheding.

A great number of workers[6, 48, 50] have suggested that some of the prompt neutrons may be emitted at the time of scission. More detailed was given by Fuller[51] and Stavinski[52]. Bowman[53] et al from their observation on the angular distribution of neutrons emitted in the sponteneous fission of Cf^{252} concluded that most of the neutrons are isotropically evaporated from the full velocity fragments. Kapoor, Rammana and Rao[54] and also Sergent[55] et al established this effect of bowman. Iyer and Ganguly[56] discussed the implications of neutron emission in the light of 'order disorder' model of the fissioning nucleus.

The emission of prompt gamma-ray is believed to occur in the final de-excitation of the fission fragments following evaporation of prompt neutrons. Statistical theory calculation[57, 48b] assumes that gamma-rays are emitted only when neutrons emission is energetically impossible. Terrell[48a] suggested that the magic and near magic fragments have low excitation energy and consequently emit almost no neutrons of greater rigidity against distortion from nearly spherical shape. The explanation for the large discrepancy probably lies in the effect of the fragment angular momentum on the neutron emission[58, 59, 56]. The gamma-ray spectrum and multiplicity that are observed suggests a cascade gamma-rays from levels of high initial spin. Prompt neutron emission can almost reduce the spin by only a few units. In accordance with the view one could expect a large gamma-ray multiplicity to be correlated with a high spin value of the fragment.

According to presently accepted notions[60, 61], the alpha-particle is emitted from the neck of the fissioning nucleus either at the instant of scission or soon after it, with certain initial energy, after which it is accelerated in the coulomb field of the fragments. The final energy acquired by the alpha-particle depends principally on the initial energy and to a lesser degree on such parameter as the kinetic energy of the fragments, the mass ratio and others. A brief discussion of emission of alpha-particle as one of the possible fission product has also been given in Chapter VI.

1.4 INDUCED FISSION IN ELEMENTS LIGHTER THAN THORIUM :

The fission of Bismuth irradiated by 15 to 22 MeV deuteron was studied by Fairhall[62]. He measured the mass yield distribution which are single humped, symmetric about mass and free from pronounced fine structure. Neuzil[63] et al studied the fission product of the separated isotope of lead by hellium ion of various energy upto 42 MeV. They observed the mass distribution to be narrow like that of Fairhail in every case, with the exception that the axis of symmetry shifted towards the lower mass value for the lighter isotope pb^{204} relative to pb^{208}. Katcoff and Hudis[64] in analysing the fission products of Bismuth, gold, silver etc. induced by 29 Gev 14 N ions, observed that there is significant increase in the fission cross-section in comparision to that done by 29 Gev proton. However, there is no indication of interaction which involve large momentum transfer to heavy target nuclei, but in case of silver target the observation indicates appreciable momentum transfer. Similar results were also been observed by Obukhov[65] et al with tin and silver using Ne^{20} as projectile. The distribution in mass and total K.E. of fission fragments from a number of elements ranging from erbium to bismuth have been measured by Plasil and Barnet[66] using projectiles ranging from He^4 to O^{16}. They observed a general agreement with shapes and widths of the distribution, particularly in the cases which involved small angular momenta and small nuclear temperature with those calculated from approximate version of liquid drop of model.

The works of Britt[67] et al firmly supports the hypothesis that there is a symmetric mode of fission dominant for fissioning nuclei near Bismuth and asymmetric mode is dominant above thorium, and a mixture of two for nuclei in between. Their data show clearly that symmetric mode increases rapidly with respect to the asymmetric as excitation energy is raised. But in sponteneous and slow neutron fission the symmetric fission is sub-barrier[68]. This probably indicates that the asymmetric fragments are formed by a passage of the fissioning nucleus through an asymmetric saddle point with subsequent dynamic effects which give a tendency towards symmetric shape.

Fission has been observed in the elements even lighter than the lightest one by Kelly and Wiegand[69] and Nervik and Sea-borg[70] and others. The cross section here are very small so small that it is difficult to study this fission. It might be worth trying to induce fission in these very light elements with heavy ions since they seem to be so effective in producing fission. In any case it seems clear that the region of the periodic table around lead deserves considerable further study because it could then be ascertained, the role played by angular momentum effect about fission threshold.

In fact, almost all the nucleus can be made to undergo fission provided it is supplied with sufficient amount of excitation energy.

The fission of medium weight nuclei ($z < 70$) irradiated by 120 MeV neutron was first studied by Dzhelepov[71] in the year 1950 using ionisation method of detection. Using radio-chemical technique of measurement, Lavrukhina[72] et al analysed the fission product of antimoney (z = 51) induced by 660 MeV protons. Bychenkov[73] et al using nuclear emulsion investigated the fission product of tungsten (z = 74) irradiated by 660 MeV proton. Using proton as projectile with varying energy, Shamov[74], Baker[75], Makawaska[76], Deka[77] et al studied the fission phenomenon of silver (z = 47) and bromine (z = 35) using emulsion technique. Their works were mainly concentrated in estimating range, energy, charge and mass of the fissioning nucleus. Recently, the fission of medium mass nuclei induced by heavy ions have been studied by Cabot[78] et al. Here the main interest is to study the variations of fissilities of nuclides undergoing fission with respect to their charges and masses and also to study the effect of angular momentum contribution towards fission.

1.5 IMPORTANCE OF THE PRESENT STUDY :

Extensive work has been done to the fission problem of heavier elements at the end of the periodic table but much less information is available about the fission of the medium weight element in the middle part of that table. Beyond establishing the mere phenomenon of nuclear fission of these elements, nothing much is known about them. Here in the present investigation attempts will be made to analyse the fission products of silver and bromine nuclei caused by interaction of high energy kaons (k^-) and antiprotons by making use of the advantages, open to nuclear emulsions. In fact, we are really in dirth of experimental findings of fission caused by strange particle like kaons. These elementary particles belong to meson class, have no spin and angular momentum. They may also add to the informations so far collected from the fission induced by protons. Again using antiproton interactions we want to study whether the characteristics of fission produced by these antiparticles are similar to that produced by the particles (protons) with the same range of energy, espicially the point of interest is to see whether the fission cross-sections during antiproton interactions with complex nuclei of emulsions increases as similar to that observed by Hussain[79] et al using mica detectors.

Although fission occurs in the process of de-excitation of the excited nucleus, but the different stages of its production is not known to us well. Here, in this work, an attempt is made to that effect also. An attempt has also been made to ascertain the idea that the production of recoils and short range spallation hyperfragments are actually the alternative processes to fission production. The discovery of unusual types of fission, namely, ternary and quaternary though is of great significance, but such a study has so long been almost confined to heavy elements. In the present study an humble effort has been made to identify and analyse these 'unusual types' in the disintegrating silver and bromine nuclei of photo nuclear emulsion.

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