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Nuclear fission phenomenon—At a glance

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Abstract. This article gives an overview of the physics of the fission phenomenon. It provides a brief introduction to the various aspects of the fission process such as liquid drop model fission barriers, different stages of the fission process, fragment kinetic energy and mass distributions, nuclear shell effects on fission barriers, fragment angular distributions and rare fission modes.

Keywords. Fission barrier; fragment mass; energy; angular distributions; shell effects; rare fission modes.

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1. Introduction

Nuclear fission which involves massive motion and subsequent division of a heavy nucleus into two nuclei with broad mass distributions, is naturally expected to be a complex nuclear reaction. The discovery of nuclear fission by Hahn and Strassmann (1939) in December 1938 was the culmination of the work of several active researchers of those days using radiochemical techniques to disentangle the transuranic puzzle. The historical story of the discovery of fission is beautifully covered in the article by D Hilscher appearing in this volume. The discovery of fission came as a big surprise, as it was very difficult to imagine in those days that a uranium nucleus with a total binding energy of about 2000 MeV could be split into two parts with the impact of a slow neutron. At first sight, it appeared as if a giant rock has fallen apart by the touch of a feather. But soon after the discovery of fission, Meitner and Frisch (1939) explained the process on the compound nucleus hypothesis and the liquid drop model. This was soon followed by the famous paper of Bohr and Wheeler (1939) which laid the foundation for a basic theory of the fission process within the framework of the liquid drop model. Although, subsequently, important advances were made with the inclusion of nuclear shell effects and other quantum properties in the various theoretical studies of the fission process, the liquid drop model (LDM) picture of Bohr and Wheeler continues to provide a very useful theoretical framework to understand and explain many gross features of the fission process.

From the shape of the curve of nuclear binding energy per nucleon versus mass number, it is easy to verify that fission of nuclei with mass number $A \geqslant 120$ will result in a release of energy. Thus, on the energy consideration alone, all these heavier nuclei should be unstable towards fission and can be expected to decay by spontaneous fission. But we know that it is not the case; what keeps these nuclei stable and as a whole is the presence of a fission barrier. In fact, the fission process is basically governed by the characteristic features of the fission barrier present in the map of the

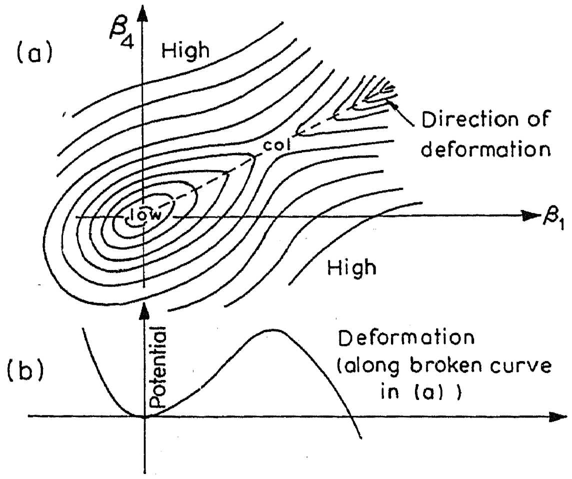

Figure 1. Liquid drop model potential energy contour of a fissioning nucleus.

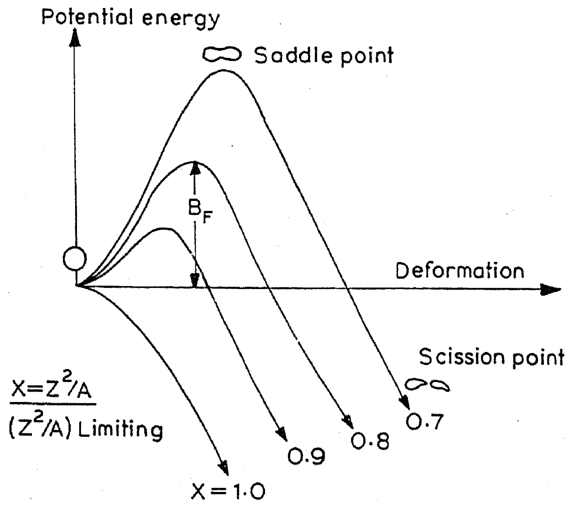

Figure 2. Potential energy vs deformation for increasing Z^2/A.

potential energy versus deformation of a nucleus. In the early sixties extensive calculations of saddle point shapes and fission barriers of nuclei were carried out by Cohen and Swiatecki (1963). Figure 1 taken from a recent review (Bjornholm and Lynn 1980) shows a schematic diagram of the potential energy contour of a fissioning nucleus as a function of the quadrupole and hexadecapole deformation parameters, as calculated from the liquid drop model. The fission barrier height, which is the maximum in the potential energy along the minimum energy trajectory for increasing nuclear elongation, depends on the fissionability parameter X, which is the ratio of the Coulomb energy E_c^0 to twice the surface energy E_s^0 of the nucleus at its spherical shape As shown schematically in figure 2, LDM predicts a rapid decrease in fission barrier heights, as the values of Z^2/A of the fissioning nucleus increase. In the spontaneous fission process, an average behaviour showing an exponential decrease of the spontaneous fission half-lives with increasing Z^2/A is indeed observed. Thus, to a first order, the general systematics of the observed spontaneous fission half-lives follow the

LDM prediction. In the case of nuclear reactions induced by energetic projectiles particularly by heavy ions, the fissioning compound nucleus can have a large spin. Theoretical calculations of saddle shapes and fission barriers of rotating nuclei by Cohen *et al* (1974) have provided a theoretical basis to understand heavy ion-induced fission reactions. A review of rotating LDM calculations with particular reference to heavy ion-induced fission by F Plasil can be found elsewhere in this volume. In recent years, Moretto and coworkers have made an important theoretical generalization towards a unified view in which fission, complex fragment emission and light particle emission are seen as a part of a single process and a comprehensive review paper on this subject by L Moretto is included in this volume.

2. Different stages of the fission process

Figure 3 schematically represents the time involved in passing through the various stages of the fission process. It also indicates at what stage different fission characteristics are determined. The scission point represents that stage of the process where the two nascent fragments are barely influenced by each other's nuclear forces. Although the fission barrier height is much smaller than the total energy released in fission, it is the fission barrier which controls the fission process. The spontaneous fission probability, the fission cross-sections and the fission fragment angular distributions are all determined by the potential energy landscape around the fission barrier. In addition to the fission barrier characteristics, the dynamics from saddle to scission is important in determining the fragment mass and charge distributions. The light charged particles emitted in fission seem to originate from around the scission configuration. A bulk of the prompt neutrons are emitted from the excited fission fragments after 10^{-20} s, when the fragments have acquired their full velocities under the mutual Coulomb repulsion. Some neutrons may be emitted during the time of nuclear dynamics to the scission point configuration and before the fragments acquire their final velocities. The fraction of this type of neutrons, although very small in low energy fission, is found to be large in heavy-ion induced fission.

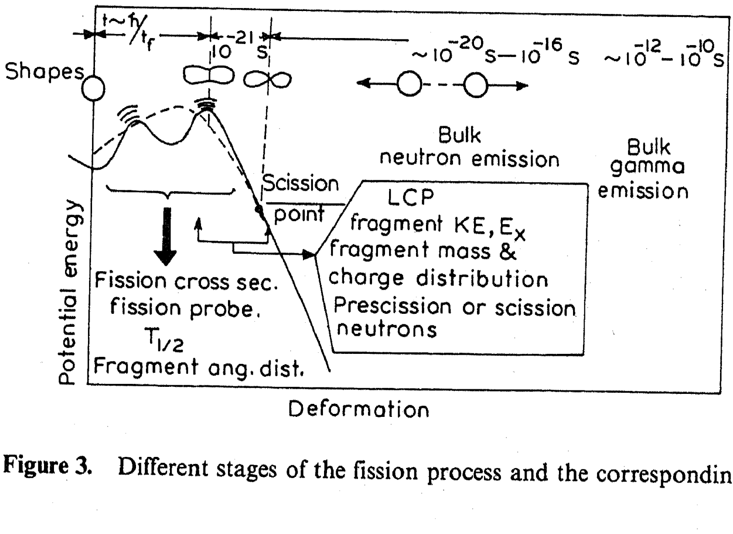

Figure 3. Different stages of the fission process and the corresponding time scales.

3. Fragment kinetic energy and mass distributions

The fragment kinetic energy is expected to be determined mainly by the Coulon energy of the scission configuration. But, depending on the extent to which the moti from saddle to scission is damped, one can also expect some prescission kinetic ener which will also get added to the Coulomb energy at scission to give the observ fragment kinetic energy. The role of energy dissipation or viscosity in the dynami from saddle to scission has been extensively disucssed in literature but no defini conclusion about the magnitude of the nuclear viscosity can be deduced from t measured fragment kinetic energies alone (Sierk and Nix 1980). It is for this reaso that studies on neutron emission in heavy ion-induced fission have turned out to quite valuable for understanding the magnitude of nuclear viscosity.

Perhaps the most striking feature of the fission process is the observed ma asymmetry in the fragment mass distributions for actinide fissioning nuclei and th has also been one of the most intricate puzzles of the fission process. More details o the mass distribution are available in the article on recent radiochemical studies o fission process by Satya Prakash appearing in this volume and the references cite therein. The various theories of the fragment mass distributions which have been p forward, from time to time, all rely on the stability of closed nuclear shells in spheric or deformed fragment nuclear configurations or on the lowering of the outer barrier the double-humped fission barrier for mass-asymmetric shapes (for more details se review by Hoffman and Hofmann (1974). A satisfactory and universally accepte answer has still not been found to the question at what stage is the mass distributio determined. However, it is realized that the dynamics from saddle to scission shoul be incorporated in any realistic model of the mass division in fission. Based on th suggestion of Ramanna (1964) it has been shown in the studies carried out at Tromba that by incorporating nucleon exchange between the two halves of the fissionin nucleus one can account for the observed mass asymmetry (Ramamurthy an Ramanna 1969; Prakash *et al* 1980). The role of nuclear exchange processes in fissio is presented in an article by Ramamurthy and Ramanna in this volume. Ne experimental data on the fragment mass distributions of fermium isotopes hav brought to light a sudden change in the behaviour of the mass distributions aroun $A = 258$. This feature appears to be related to the behaviour of the potential energ landscape from saddle to scission (Möller *et al* 1986).

4. Nuclear shell effects on fission barriers

Although the liquid drop model met with impressive success in explaining the general systematics and has contributed much to the development of the first-order theory of fission, it failed to explain many features of the process. For example, the existence of fission isomers, the intermediate structure in fission resonances and the observed near-constancy of the fission barriers with Z and A in the actinide region could not fit into the LDM picture. These observations are now well understood with the introduction of the concept of deformed nuclear shells leading to double-humped nature of the fission barrier for the actinide nuclei.

The importance of the effect of nuclear shells of spherical shapes in calculating the nuclear potential energy was first pointed out by Myers and Swiatecki (1966).

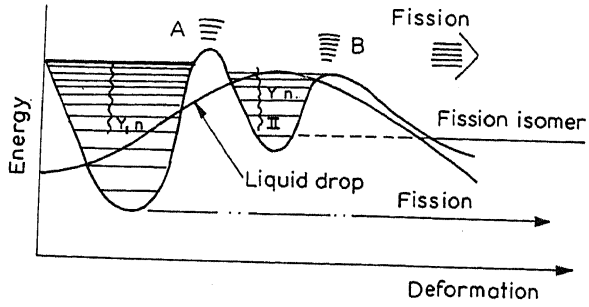

Figure 4. A schematic diagram of double-humped fission barrier.

Subsequently, the work of Strutinsky (1967) along these lines has been an important landmark in fission research. Strutinsky developed a method for calculating shell correction energies to the LDM potential surface starting from shell model single particle levels and showed that the generalized nuclear shell effects in deformed nuclear shapes lead to a double-humped fission barrier for actinide nuclei as shown in figure 4. The Strutinsky method has been discussed and reviewed from time to time in recent literature. This volume includes a review article on shell structure in deformed nuclei and nuclear fission by V M Strutinsky.

The double-humped fission barrier explains several features observed in fission. The spontaneously fissioning isomers are now well understood to be shape-isomers corresponding to the deformation of the second minimum of the double-humped potential energy surface. In general, γ-deexcitation of a nucleus, formed with the second minimum deformation to its normal ground state shape, will be hindered due to the presence of the first barrier and the predominant mode of decay of such a nucleus will be the spontaneous fission decay by penetration through the second barrier. Considering that the second minimum is at an energy higher than the ground state and the penetration involves only a thin second barrier, spontaneous fission lifetimes of these isomers are drastically reduced over ground-state spontaneous fission lifetimes, as has been observed. In the case of double-humped potential energy surface, in addition to the spectrum of compound nucleus states (class I states) at the first minimum deformation, there will also exist a spectrum of states (class II states) in the second well. The intermediate structure effects observed in subthreshold fission cross-sections are now well understood on the basis that each time spin, parity and energy of class I states match with those of class II states the fission probability is enhanced in the corresponding slow neutron resonances. The article on the topography of the nuclear fission barrier by J E Lynn included in this volume summarizes the implications of the double-humped fission barrier on the fission phenomenon.

Inclusion of nuclear shell effects in the calculation of nuclear potential energies leads to another important result. If one extrapolates on the basis of LDM the observed general trend of decrease in the spontaneous fission half-lives with increasing Z^2/A to very heavy nuclei, for $Z^2/A \geqslant 48$ the nuclei are expected to have vanishingly small half-lives and therefore cannot exist. However by including the ground-state shell correction energy to the LDM potential energy, superheavy nuclei in the vicinity of next closed shell for $Z = 144$, $N = 184$ are predicted to have appreciable fission barrier heights. These nuclei may therefore have sufficiently long lifetimes to become observable. Figure 5 shows the predicted island of these relatively stable superheavy

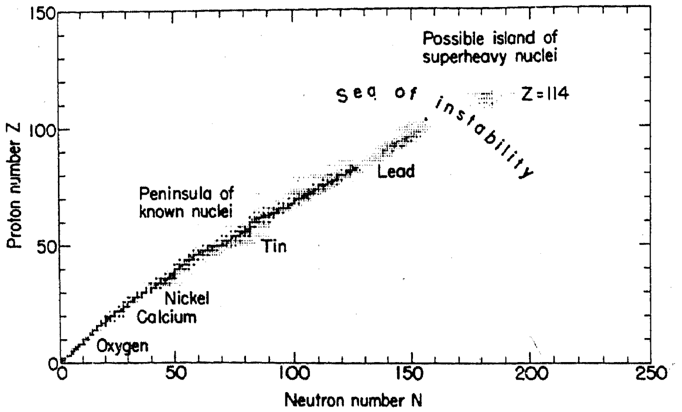

Figure 5. Predicted island of superheavy nuclei around the doubly closed shell $Z = 11$ $N = 184$.

nuclei. For further details on this subject see recent reviews (e.g. Flerov an Ter-Akopian 1984).

5. Fragment angular distributions

The foundation of our present understanding of fragment angular distribution wa laid by Bohr (1955) with the application of the unified model to the highly deforme transition state nucleus passing over the saddle point on its way to fission. Boh postulated that a fissioning nucleus spends a sufficiently long time at the fissio transition state to define a spectrum of quasi-stationary states at the saddle point. Thi model proved to be highly successful in explaining the fragment angular distribution at very low energies on the basis of available quantum states at the saddle poin Halpern and Strutinsky (1958) extended this model to the statistical regime of highe excitation energies with spectacular success. Over the years, fission fragment angula distribution studies have turned out to be extremely useful in obtaining informatio about the shape of the nucleus at the fission transition state. One has also learnt abou the washing out of the shell effects with excitation energy in an effort to understan fragment angular distributions taking into account the double-humped nature c fission barrier. Studies on fragment angular distributions in heavy ion-induced fissio have yielded information about the *K*-equilibration during the fusion dynamics. It ha also been shown that in addition to quasifission and fast fission processes, anothe process of "pre-equilibrium fission" can be an important fission-like reaction in heav ion-induced reactions (Ramamurthy and Kapoor 1985). A review article on th fragment angular distributions by Kapoor and Ramamurthy has been included in thi volume for detailed studies.

6. Rare fission modes and energy dissipation

In recent years there has been considerable interest in the study of rare fission event such as light-charged particle accompanied fission, low energy symmetric fission, col compact fission corresponding to a window of high fragment kinetic energies, an cold-deformed fission with window on low-fragment kinetic energies. Study on light particle accompanied fission provides information on the scission configuration as well as dynamics of the fission process at the instant of their emission (see for example Kapoor and Nadkarni 1985 and references cited therein). The subject of light-charged particle emission in fission is reviewed in the article by Sinha, Nadkarni and Mehta appearing in this volume. The new developments related to cold compact fission have recently been discussed by Hasse (1987) with regard to experimental data as well as possible theoretical explanations. Considerable theoretical studies have been carried out in recent years to investigate the dominant energy dissipation mechanism that is appropriate for the description of the dynamical descent of a fissioning nucleus from saddle to scission or for the macroscopic heavy-ion collisions. The energy dissipation from saddle-to-scission can arise due to two-body collisions between individual nucleons or by one-body dynamics involving interaction between the nucleon and the mean field created by all the other nucleons, or by a combination of these two types of mechanisms. In the two-body dissipation mechanism, the magnitude of the viscosity comes out to be small leading to extended scission configurations with considerable prescission kinetic energy. On the other hand, the one-body dissipation mechanism leads to high dissipation, more compact shapes and very small prescission kinetic energy. Extensive theoretical studies on these dissipation mechanisms have been reported in recent years. Comparison of experimental data on probable fission fragment kinetic energies with those calculated using wall-and-window one-body dissipation and two-body dissipation mechanisms shows that the observed variation of the average fragment kinetic energies with Z^2/A can be explained by both the mechanisms, but their predictions for the prescission kinetic energies and for the saddle-to-scission time are different.

Interesting information regarding energy dissipation in heavy-ion collisions and in the fission process can also be deduced from the study of fragment-neutron angular correlations in fission. From these measurements, one deduces the average number of prefission neutrons and a comparison of this number with that expected on the basis of statistical calculations shows that the average number of prefission neutrons is much larger than predicted from the statistical model calculations. It has been inferred that in heavy-ion induced fusion-fission reactions, excess neutrons are emitted during the dynamics from the stage of formation of the di-nuclear system to the scission stage. Therefore information about energy dissipation can be deduced from such studies (Hinde 1986; Gavron 1987; Kapoor 1988). This subject is covered in the review article on prescission particle and γ-ray emission in heavy ion-induced fission by Newton included in this volume.

7. Concluding remarks

To sum up, as we are about to commemorate fifty years of the discovery of fission, we can feel greatly satisfied by the fact that the study of fission process has considerably enriched nuclear physics by providing information on several aspects of nuclear behaviour which cannot be studied otherwise. Nuclear shell effects in highly deformed nuclear shapes such as those encountered during the fission process and the study of topology of nuclear potential energy surfaces and the resulting dynamics of a fissioning nucleus can be cited as important examples of this type. Several studies of nuclear fission phenomenon which are aimed at probing the dynamics of the fissioning system are being taken up in recent years, and these studies are expected o remain exciting and fruitful areas of further research. There are still many aspects of both nuclear macrophysics and nuclear microphysics which are yet to be explor d through fission studies.

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