

**DYNAMICS OF FUSION-FISSION AND
RELATED PHENOMENA AT
LOW ENERGIES**

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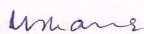
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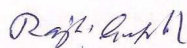
*My beloved parents and to my husband
Kanwar Rahul*

CERTIFICATE

This is to certify that the thesis entitled " **DYNAMICS OF FUSION-FISSION AND RELATED PHENOMENA AT LOW ENERGIES**" being submitted by **Mrs. Shefali Kanwar** for the fulfillment of the requirements for the award of Degree of Doctor of Philosophy in the School of Physics and Materials Science, Thapar University, Patiala, is a record of the candidate's own work carried out by her under my supervision. The matter presented in this thesis has not been submitted in part or full for the award of any degree in any university or institute.

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5. Evaporation residues, fission and quasi-fission cross-sections in the decay of $^{202}\text{Pb}^*$ using dynamical cluster decay model, **Shefali Kanwar**, BirBikram Singh, Manoj K. Sharma and Raj K Gupta, DAE Nucl. Phys. Symp., IIT Roorkee, Uttarakhand, Dec., **53**, 497 (2008).
 6. Decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca}+^{154}\text{Sm}$ reaction using Dynamical Cluster-decay Model. Manoj K. Sharma, **Shefali Kanwar**, BirBikram Singh, Manoj K. Sharma and Raj K Gupta, DUBROVNIK09, Croatia .
 7. Entrance channel effects in the decay of $^{82}\text{Sr}^*$ using Dynamical Cluster Decay Model, Manoj K. Sharma, Ramneek Kaur, **Shefali Kanwar**, and Raj K Gupta, NTSD-09 TU, Patiala, **16**, 114 (2009).
 8. Shell closure ($N_c = 126$) effect in the decay of $^{206,210}\text{Po}^*$ formed in heavy ion reaction, **Shefali Kanwar**, Manoj K. Sharma and Raj K Gupta, NTSD-09 TU, Patiala, Oct (2009).
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 10. Decay of $^{196}\text{Pt}^*$ formed in inverse kinematic $^{132}\text{Sn}+^{64}\text{Ni}$ reaction using the Dynamical cluster- decay Model, **Shefali Kanwar**, Manoj K. Sharma and Raj K Gupta, DAE Nucl. Phys. Symp., BARC Mumbai, **65**, 368 (2009).

11. Decay of $^{176,182,188,196}\text{Pt}^*$ nuclei using the Dynamical Cluster-Decay Model, Manoj K. Sharma, **Shefali Kanwar**, and Raj K Gupta, American Institute of Physics Proceeding **1265**, 37, (2010).

Abbreviations

Cluster Radioactivity (CR), Symmetric Fission (SF), Near Symmetric Fission (nSF), Evaporation Residue (ER), Fusion-Fission (FF), Quasi Fission (qf), Preformation probability P_0 , Penetration probability P , Scattering Potential ($V(R)$), Fragmentation potential ($V(\eta)$), Liquid drop energy (V_{LDM}), Proximity potential (V_P), Coulomb potential (V_C), Angular momentum potential (V_ℓ), Light particle (LP), Intermediate mass fragments (IMF), Hauser Feshback (HF), Centre of mass energy ($E_{c.m.}$), Compound nucleus energy (E_{CN}), Mass distribution (MD), Isospin ratio (N/Z), Quadrupole deformation (β_2), Octupole deformation (β_3), Hexadecapole deformation (β_4), Statistical saddle-point model (SSPM), Binding energy (B.E), Potential energy surfaces (PES).

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Abstract

The aim of present work is to study the possible decay modes of different nuclear systems at low energies. In the process, issues related to fine-structure/ sub-structure of fission fragments, shell effects, angular momentum, deformation and orientation effects, etc., are investigated. The role of deformations in cluster radioactivity (CR) have also been studied extensively. The Dynamical Cluster-decay Model (DCM) is used to study the decay of heavy nuclear systems formed in heavy ion reactions. It is relevant to mention here that the contribution of angular momentum, nuclear deformations and orientations are included in DCM. For all the systems studied in this thesis, DCM results find nice comparisons with the experimental data over a wide range of energies. The DCM with angular momentum (ℓ)=0 and temperature (T)=0 approximations is used to investigate the role of deformation in CR. The thesis is divided into seven chapters.

Chapter 1 contains the general introduction to present work. An overview of current research status of fusion-fission and related aspects is given. Beside this, a brief account of low energy nuclear reactions is explained where emphasis is laid on deeper understanding of compound nuclear systems. The role of nuclear shapes i.e. the effects of deformation and orientation on formation and decay of a nuclear system is discussed.

Chapter 2 gives the details of the methodology used in this thesis. The DCM which is used to calculate the decay properties such as decay cross sections, kinetic energies, etc., has been discussed in detail. In DCM, besides the temperature and angular momentum effects in the decay of excited compound nuclei, the deformation and orientation effects of decay products are also taken care of. The DCM is based on the Quantum Mechanical Fragmentation Theory (QMFT), and hence a brief overview of the same is also given. The method of calculating the fragmentation potentials, the collective potentials, and kinetic energy part of the Hamiltonian are discussed, together with the solution of the stationary Schrödinger wave equation. The details are given for the effects of deformed and oriented nuclei in the proximity, Coulomb and angular momentum potentials. The DCM is used to study the decay of hot and rotating compound nucleus formed in heavy ion reactions, whereas DCM with $T=0$, $\ell=0$ approximations, known as Preformed Cluster Decay Model (PCM), is used to study the ground state decay of nuclei, the cluster radioactivity, in trans-lead region.

In **Chapter 3**, the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction at different center-of-mass energies is studied using the dynamical cluster-decay model (DCM) for spherical fragments. The calculated results show an excellent agreement with experimental data for the fusion-evaporation residue cross-section σ_{ER} together with the fusion-fission cross-section σ_{FF} , and the competing, non-compound-nucleus quasi-fission cross-section σ_{QF} . Also the prediction of two fission windows, the symmetric fission (SF) and the near symmetric fission (nSF) whose contribution is more at lower incident energies, suggests the presence of a fine structure effect in the

fusion-fission of $^{202}\text{Pb}^*$. The nSF window (responsible for quasi-fission (QF) process) is shown to be due to the presence of shell-effects (magic shells) in the mass distribution of $^{48}\text{Ca} + ^{144}\text{Sm} \rightarrow ^{202}\text{Pb}^* \rightarrow A_1 + A_2$ reaction. As a further verification of this result, no QF component has been observed in the decay of $^{192}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction in agreement to experimental observation.

In **Chapter 4**, the decay of Pt isotopes $^{176,182,188,196}\text{Pt}^*$ formed by $^{64}\text{Ni} + ^{112}\text{Sn}$, $^{64}\text{Ni} + ^{118}\text{Sn}$, $^{64}\text{Ni} + ^{124}\text{Sn}$ and $^{132}\text{Sn} + ^{64}\text{Ni}$ reactions has been studied using the Dynamical Cluster-decay model (DCM). The interesting aspect of this study is that, the data for evaporation residue (ER) and fusion-fission cross-sections is available on either side of Coulomb barrier energy. Here we observe that different isotopes of Pt^* display different decay patterns. With the increase in number of neutrons, i.e., with the increase of N/Z ratio of CN, the characteristics of the emitted light particles (the ER) change and the fission mass distribution changes from a symmetric fragmentation to an asymmetric fragmentation. The DCM based ER cross-section find nice comparison with experimental data, whereas, the σ_{fiss} calculations show a significant contribution of quasi-fission (σ_{qf}) at the highest one or two energies. Then the total fusion cross-sections/ ($\sigma_{ER} + \sigma_{fission} + \sigma_{qf}$) calculated on DCM fit the data nicely for all the four isotopes of Pt^* over a wide range of energies. Specifically, other model calculations, like the BPM, CCFULL and DC-TDHF, are available for the $^{132}\text{Sn} + ^{64}\text{Ni} \rightarrow ^{196}\text{Pt}$ reaction and the DCM results are found better than these predictions, in particular at sub-barrier energies.

In **Chapter 5**, the dynamical cluster-decay model is used for the first time to

study the decay of odd-mass nuclear systems $^{213}\text{Fr}^*$ (with $N=126$) and $^{217}\text{Fr}^*$ (with $N=130$) formed in $^{19}\text{F} + ^{194,198}\text{Pt}$ reactions with spherical as well as quadrupole (β_2) deformations having "optimal" orientations of hot (compact) configurations. As $^{213}\text{Fr}^*$ is more fissile than $^{217}\text{Fr}^*$, so σ_{fiss} is more for $^{213}\text{Fr}^*$ over the entire measured energy range as compared to that for the less fissile $^{217}\text{Fr}^*$. Interestingly, the calculated fission distributions for both $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ are symmetric for spherical nuclei and asymmetric for β_2 deformation included. The role of deformations in the decay of $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ nuclear systems can be assessed from the comparative behavior of mass fragmentations. The measured anomaly in fission anisotropy reported in case of $^{213}\text{Fr}^*$ can be understood in terms of either the possible role of magic $N=126$ shell of the compound nucleus or the presence of a non-compound nucleus (nCN) component, like the quasi-fission (qf), in fission cross-section. For quadrupole deformed and "optimal" oriented fragments, the calculated fission cross-sections (as well as the evaporation residue cross-sections) match the data nearly exactly, leaving no room for the nCN, qf component in fission cross-sections. Therefore, measured anomaly in the fission anisotropy for $^{213}\text{Fr}^*$ can be due to the role of magic shell i.e $N=126$. As the fragmentation process for spherical and or β_2 deformations is almost identical for $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$, nothing conclusive can be said about the role of magic shell $N=126$. However, it will be of interest to include further the higher multipole deformations and "generalized orientations" in the decay process of these nuclei in order to establish the explicit role of $N=126$ in the decay of $^{213}\text{Fr}^*$ nucleus, if any.

In **Chapter 6**, we have used the Preformed Cluster Model (PCM) of Gupta and

collaborators, to study the role of deformations/orientations in all the measured cluster-decays, including the very recent experiments for the decay of ^{14}C and ^{15}N from ^{223}Ac and ^{34}Si from ^{238}U . It has been observed that β_2 alone with optimal orientations is good enough to fit the experimental decay half-life times $T_{1/2}$ for majority of measured clusters-decays. However higher multi-pole deformation effects seems essential for ^{14}C decays of ^{221}Fr , $^{221-224,226}\text{Ra}$, and ^{225}Ac . Because the PCM treats the cluster-decay process as the tunnelling of a preformed cluster, the deformations and orientations of nuclei modify both the preformation probability P_0 and tunnelling probability P , and hence the decay half-life, considerably. It has been established through this study that the deformation and orientation effects are extremely desirable, in addition to the shell and Q-value effects.

Finally, in **chapter 7**, we summarize the results of this work and give a brief outlook.

Chapter 1

Introduction

Since ages, consistent and rigorous efforts of human brain have resulted into deep understanding of a number of natural phenomena and the nature itself, to a large extent, which is generally referred as physical sciences. Explorations of composition of matter lead to its better interpretation in terms of building blocks like molecule, atom and atomic nucleus, which are having further substructures. The atom is a basic unit of matter consisting of a dense, central nucleus surrounded by a cloud of negatively charged revolving electrons. Further, the atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons. The present perception of an atom would not have been possible without a number of landmark discoveries and theoretical modeling during the late 19th and early 20th centuries, namely, the pioneering discoveries of radioactivity, the electron, the atomic nucleus, the Rutherford-Bohr model of the atom followed by the advent of quantum mechanics developed by numerous physicists like de Broglie, Schrödinger, Heisenberg, Pauli, Dirac and others.

The nucleon-nucleon interactions between nuclei are quite relevant and interesting to understand the nuclear forces existing between neutrons and protons inside a nucleus. One nucleus will spontaneously transform into a different nucleus if the final state nucleus is more stable and if the laws of physics allow the transformation, the process which is often called radio-active decay and usually accompanied by the release of ionizing radiations. Most of the matter found naturally on Earth is stable and does not undergo this transformation. Nuclei that exhibit this behaviour are said to be unstable or radioactive. This process of nuclear transformation carries significant information about nuclear dynamics as well as its structure. Nuclei can undergo transformation artificially in nuclear reactions. The first experimental demonstration of nuclear reaction was carried out by Rutherford in 1919. Since then experimental techniques in the field of nuclear reactions have improved immensely. Formerly, in the study of nuclear reactions, projectiles used were basically the alpha particles from natural radioactive substances. The discovery of neutron in 1932 caused an impetus in the nuclear reaction experiments. Low energy neutrons can easily penetrate Coulomb barrier and cause nuclear reactions. Later on, the advent of advanced heavy ion beams have revived our understanding regarding nuclear reaction dynamics in general and nuclear structure in particular.

The field of physics that studies the building blocks and interaction of atomic nuclei is defined as nuclear physics. A principal research tool of nuclear physics is a high-energy beam of particles, such as protons, neutrons, α -particles or heavy ions, directed as projectiles against nuclear targets. By analyzing the directions and energies of the recoiling particles and any resulting nuclear fragments, nuclear physi-

cists can obtain details of nuclear structure, the strong force that binds the nuclear components together, and the release of energy and mass/charge of fragments from the nucleus. In nuclear physics all the known natural forces can be studied simultaneously, and hence forth provides a natural laboratory for the testing of many fundamental symmetries and laws of nature along with their possible extension for meaningful applications. Nuclear physics is unique in the context that it acts as an intermediate step for the most fundamental and the applied topics. For example it has found broad applications in the field of science, technology, nuclear engineering and nuclear medicine, etc. Presently a lot of work is being done at low, intermediate and high energy domain of nuclear reactions. In the present thesis, we confine ourselves to low energy nuclear reactions. It is relevant to mention here that the low energy nuclear physics is a prime training ground for those interested in the nuclear reaction dynamics and the related problems.

A heavy nucleus can contain hundreds of nucleons which mean that with some approximations it can be treated as a classical system, rather than a quantum-mechanical one. As a result the liquid-drop model was proposed which is able to reproduce many features of nuclei, including the general trend of binding energy with respect to mass number, as well as the phenomenon of nuclear fission. Much of current research in nuclear physics relates to the study of nuclei under extreme conditions such as high spin and excitation energy. Nuclei may also have extreme shapes or extreme neutron-to-proton ratios. In order to understand the formation and decay process of these exotic nuclear species, the deformations, orientation, angular momentum, excitation energy etc. of nuclei and their quantum mechanical

treatment becomes essential.

1.1 Nuclear Reactions

A nuclear reaction is the process in which two nuclei or nuclear particles collide to produce products different from the initial particles. In principle a reaction can involve three or more than three colliding particles, but the probability of three or more nuclei to meet at the same time at the same place is much less than for two nuclei, therefore such an event is exceptionally rare. Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. For a nuclear reaction to occur in laboratory, the nucleons in the incident nucleus, or projectile, must interact with the nucleons in the target. Therefore the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy "barrier" is called the Coulomb barrier.

When a collision occurs between the incident particle/nucleus and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiations or nucleons. A nuclear reaction is described by identifying the incident particle, target nucleus, and its reaction products. It is broadly divided into three main categories;

1. Fusion Evaporation residue cross-section
2. Fusion-Fission cross-section

3. Quasi-Fission or Deep Inelastic collision cross-section

The process of Fusion evaporation occurs when a projectile beam is incident on a target, creating a compound nucleus which is relatively stable but excited with fairly large angular momentum. This compound nucleus now loses some of this excess energy in the form of α -particles, neutron, proton and γ -rays. Normally if, available energy is sufficiently large then α -particle is emitted otherwise smaller particles like neutron, protons etc. are emitted. As the system is in excited state so the (ground-state) stable condition is achieved via emission of γ -rays.

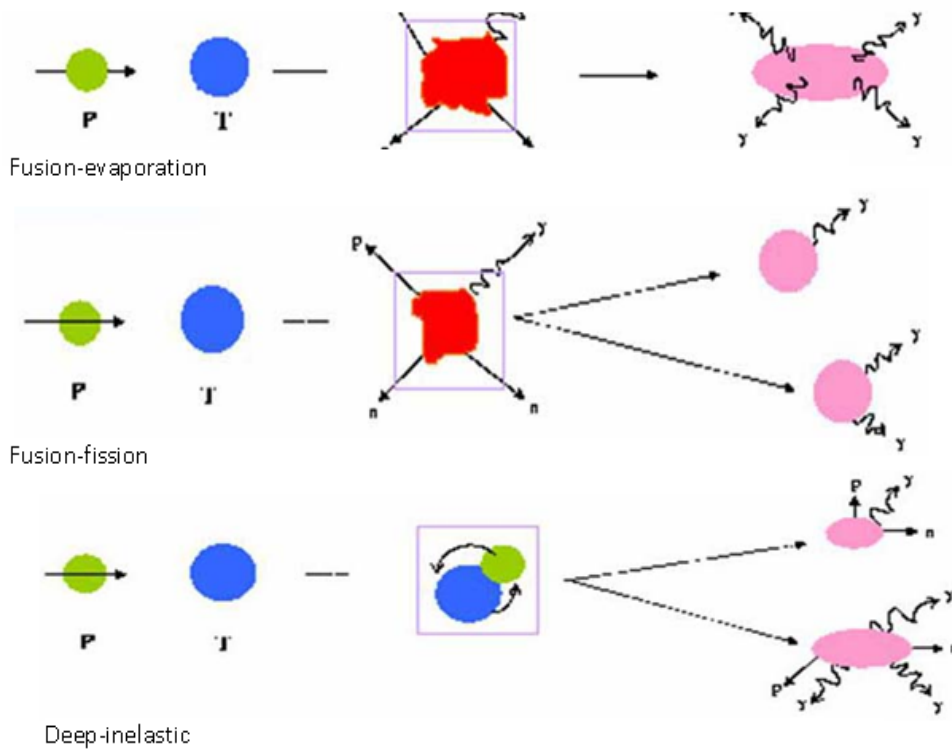


Figure 1.1 Different types of nuclear reactions.

In Fusion-fission process the compound nucleus is normally in an excited state

and excitation energy depends on the energy of fusion reactants. It loses this excitation energy in various ways. For the heavy nuclear systems the most probable decay mode of the compound nucleus is fission, due to its instability against centrifugal repulsion. However for light compound systems with $A < 80$ there is a competition between decay modes (Fission versus fusion evaporation residue).

The third main type of reaction is the Deep-inelastic reaction. Deep inelastic collisions of nuclei are very energetic collisions. Such reactions involve heavier ions and generally take place at intermediate impact parameter. For large impact parameter they go over into the direct or quasi-elastic reaction and for small impact parameter into fusion. The important difference between ER, fission and deep inelastic reactions is that the compound nucleus (CN) formation take place in first two whereas third one is non-compound nucleus reaction. With this non-compound nucleus (nCN) reaction if the emitted products are identical with the formation partners, the reaction is called as Quasi-fission reaction or quasi-fission process. The schematic diagrams of three reactions are shown in Fig.1.1.

In general, the compound nucleus (CN) formed in low energy reaction is normally in the excited state which decays by emitting multiple light particles, LPs (n , p , α) and fusion-fission processes. In some cases depending on reaction conditions, the fusion-fission process competes with QF or DIC. The formation and decay process of CN alongwith the competing QF or DIC is depicted in Fig. 1.2, where the possibility of using cluster-decay for fusion-fission process is also suggested. In fact, this concept of preformed clusters is later extended in DCM to both the light particles and fusion fission processes.

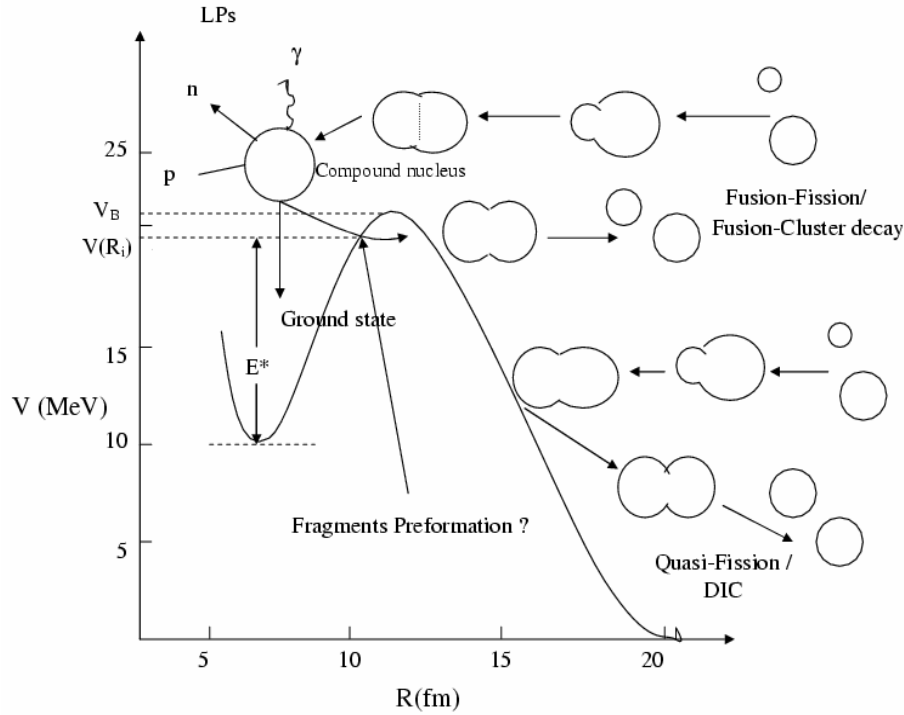


Figure 1.2 Schematic diagram for dynamics of the colliding nuclei playing around Coulomb as well as nuclear interaction potential.

1.2 Deformation and orientation effects

In nuclear reactions, for successful formation of nuclei, a deep understanding of fusion-fission reactions is extremely important. Fission phenomena of atomic nuclei have been extensively investigated, but many related aspects are not yet well understood. Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and lighter nuclei, which may eventually go to ground states via the emission of photons (in the form of gamma rays). Fission is a form of nuclear transmutation in which the resulting fragments are not the same elements as the reactants. Since fission fragments are many times deformed, the deformation properties of fissioning nuclei and their fragments are

important.

The effects of deformation parameter of atomic nuclei seem to play important role in the formation and decay process of a nuclear system. The availability of deformed shells and related aspects has put new life in low energy nuclear reactions and many new phenomena are emerging because of explicit role of nuclear deformations and orientation. Historically, speaking, the shape of nucleus was first investigated by Schuller and Schmidt [1] in 1935 by determination of nuclear electric quadrupole moment from hyperfine structure in atomic spectra. The nuclear electric quadrupole moment measures the deviation of charge distribution from a spherical shape and hence provides information about nuclear shape.

Nuclei have extreme shapes, the higher multi-pole deformations, $\beta_\lambda(\lambda=2,3,4)$ as shown in Fig.1.3 or extreme neutron-to-proton ratios where the term β is a measure of how much the scissioning nucleus deviates from the spherical shape. In many respects spherical nuclei are exceptional, as the vast majority of nuclei are deformed. Many nuclei are only slightly deformed, and so can still be well described by spherical nuclear models. However, for nuclei with mass number A in the range $150 < A < 190$ and $A > 220$, deformation can no longer be ignored. To lowest order, most deformed nuclei can be approximated as quadrupole deformed (i.e. a prolate or oblate ellipsoid). Higher order deformations, such as octupole (β_3) and hexadecapole (β_4) are also possible, as are triaxial deformations and other more exotic shapes.

Deformation alters the properties of single-particle wave functions from those of the spherical shell model. In particular, the breaking of spherical symmetry changes the degeneracy of energy levels, and allows for collective rotation of the nucleus. The

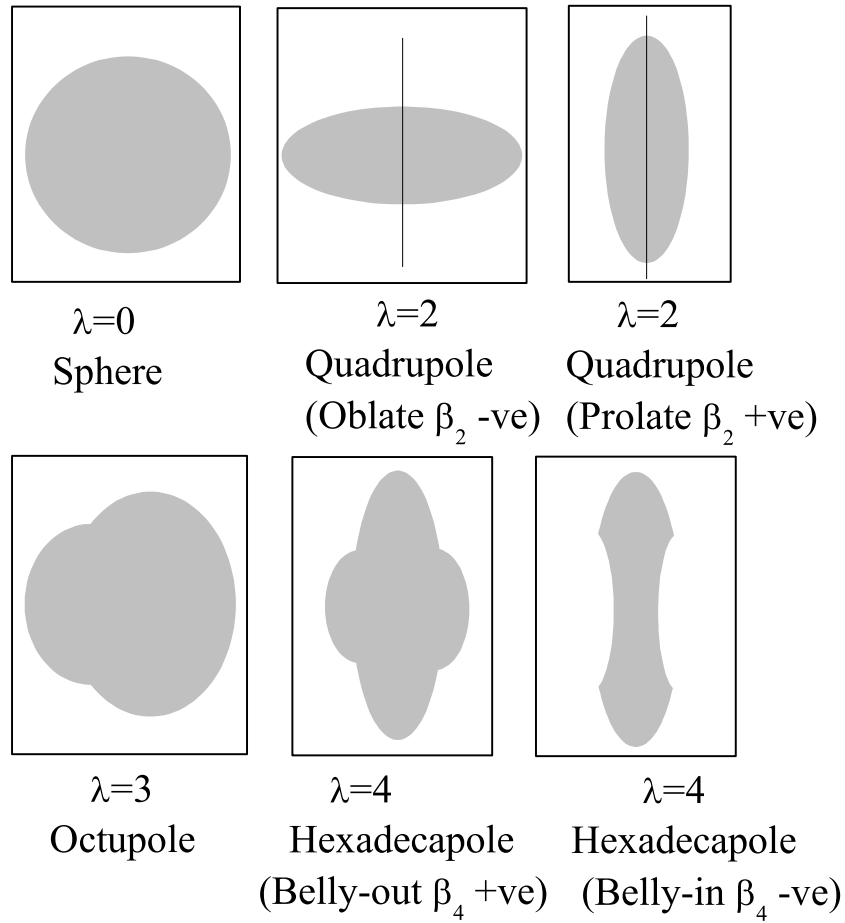


Figure 1.3 Schematic diagram for various multipole deformations in nuclei. For quadrupole deformations, there are two choices i.e. nuclear matter rotates on short axis (oblate) and on long axis (prolate). Similarly hexadecapole has two choices of positive (belly out) and negative (belly in) sign.

presence of rotational excited states and the detection of large quadrupole moments are good indications that a nucleus is deformed. Figure 1.4 shows a schematic configuration of two (equal/ unequal) axially symmetric deformed, oriented nuclei, lying in the same plane ($\phi = 0^\circ$), for various θ_1 and θ_2 values in the range 0° to 180° . Rest of the details of Figure 1.4 are given in chapter 2 [2]- [4]. Nuclear reactions, with deformed nuclei are engaged, are widely applied for the synthesis of superheavy elements in many laboratories around the world. The depth and the width of the capture well in the nucleus-nucleus interaction potential, as well as the

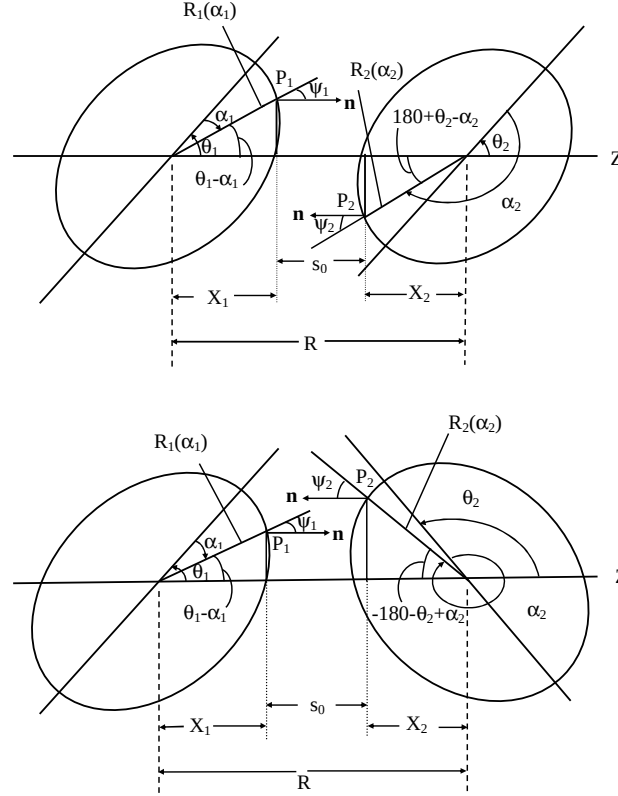


Figure 1.4 Schematic configurations of two (equal/ unequal) axially symmetric deformed, oriented nuclei, lying in the same plane and for various θ_1 and θ_2 values in the range 0° to 180° . The θ 's are measured in anti-clockwise from the colliding axis and the angle α 's in clockwise from the symmetry axis.

barrier height, are known to play a dominant role in the formation of a compound nucleus in fusion reaction. This aspect is associated with the necessity to overcome the barrier that exists between two separated nuclei and with a formation of a neck between contacting nuclei in the capture well, as well as with the following evolution of a shape of the nuclear system. Therefore, it is very important to study the effect of a deformation and an orientation of nuclei on the nucleus-nucleus interaction potential in order to have meaningful predictions of formation and decay paths of

nuclear reactions.

It is relevant to mention here that the distance between mass centers of the massive reactants rely on the orientation of the deformed nuclei [3]- [11]. So fusion process should be viewed in that prospective. Each fusion reaction is characterized by a specific barrier, which must be surpassed before the reaction can occur. Consequently, the fusion process is greatly affected by the relative orientations of the deformed nuclei. The fusion of nuclei below the Coulomb barrier can occur only by quantum mechanical tunnelling through the barrier. The barriers for massive nuclei are more complex than those of α 's and other light charged particles. For heavy-ion fusion the 'gentle' fusion and 'hugging' fusion have been proposed theoretically which correspond to some typical shapes of deformed and oriented nuclei (prolate deformed with positive or negative signs of hexadecapole deformations) and their relative orientations.

Normally, the compound nucleus formed has high excitation energy and carries large angular momentum. Depending on the mass, the compound nucleus losses its excitation energy by emitting certain fragments [12,13]. The compound nucleus can decay via light particle evaporation (LP's), intermediate mass fragments (IMF's), fission process and quasi fission process [14]- [17], etc. For light compound systems with $A_{CN} \approx 40-80$, the light particles emission LP's ($Z \geq 2, A \leq 4$) is very prominent (90-95 %) and is accompanied by (5-10 %) of intermediate mass fragments (IMFs $Z \geq 2, 5 \leq A \leq 20$) [18]. For the heavy nuclear system $A_{CN} \approx 200$, the most probable decay mode is fission with a very small contribution from LP's, in contrast to light compound systems. However a significant contribution of ER is measured in a few heavy systems.

1.3 Cluster Decay

Cluster radioactivity is a process in which a nucleus emits spontaneous clusters that are heavier than the alpha particle but lighter than fission fragments. The emission of clusters heavier than α -particles is not being accompanied by any neutron emission. Thus, it is a cold process (zero excitation energy) since the energy released as Q-value is completely consumed by the kinetic energy alone of the two fragments (the cluster and daughter nuclei). The clusters usually emitted in this process are the particular isotopes of C, N, O, F, Ne, Mg and Si. When the mass of the cluster becomes comparable with the mass of the daughter, fission takes place. The emitted cluster has an intermediate position between alpha decay and fission. Cluster decay was discovered in 1984 when researchers at Oxford University detected that ^{223}Ra emits one ^{14}C nucleus for every billion (10^9) alpha decays [19]. This phenomena was first predicted by Săndulescu, Poenaru, and Greiner in 1980 [20] and its study was based on Quantum Mechanical Fragmentation Theory (QMFT) [21] of Greiner, Gupta and collaborators. Since 1984, emissions of many other clusters e.g., ^{14}C , ^{15}N , $^{18,20}\text{O}$, ^{23}F , $^{22,24,25,26}\text{Ne}$, $^{28,30}\text{Mg}$ and $^{32,34}\text{Si}$, have been observed from about 20 heavy nuclear systems in mass region $A = 220 - 248$. The experimental study of cluster radioactivity was done by various different experimental groups at Berkeley, Dubna, Orsay and finally Milano to develop experimental techniques dedicated to investigate such peculiar, extremely rare decay mode of heavy nuclei. Cluster decays of some heavy and super-heavy nuclei, formed in heavy-ion cold fusion reactions, are studied within a preformed cluster decay model [22]- [25]. In theoretical method of Gupta and collaborators [2], [26]- [28] all the possible cold reaction valleys were generated by the shell closure effects in one or both the reaction partners.

The existing theoretical models generally fall under two categories: the unified fission model (UFM) and the preformed cluster model (PCM). Although the preassumptions of UFM and the PCM are completely different but both seem to be working nicely in order to understand the spontaneous decay process. The UFM considers cluster radioactivity simply as a barrier penetration phenomenon in between the fission and the α -decay without worrying about the cluster being or not being preformed in the parent nucleus. In the PCM, clusters are assumed to be preborn in a parent nucleus before they could penetrate the potential barrier with a given Q-value. The basic assumption of the UFM is that heavy clusters as well as the α -particle have equal probability of being preformed. In PCM, clusters of different sizes have different probabilities of their being preformed in the parent nucleus. Within the fission model of cluster radioactivity, the ground-state deformation effects of the parent and/or daughter, keeping the emitted cluster still spherical, were introduced by Shanmugam and Kamalaharan [29] for the finite-range Yukawa-plus-exponential potential, and for the emitted quadrupole deformed cluster, treating the daughter as spherical, by Gupta et al. [30, 31] using the double folded Michigan-3 Yukawa (M3Y) potential. The deformation effects of the daughter nucleus, as well as the higher multipole deformations, were also accounted for later with in the M3Y potential [32]. In this work we have studied the explicit role of deformations of the parent, daughter and cluster [33, 34]. More recently, Gupta and collaborators have studied exotic cluster radioactivity process with in PCM using the Relativistic Mean Field Theory (RMF) densities [35].

1.4 The Model

In the present work we have used the Dynamical Cluster decay Model adopted from Preformed Cluster Model (PCM) which find its basis in Quantum Mechanical Fragmentation Theory (QMFT) [27, 28]. In DCM, we have calculated the temperature dependent binding energies by modifying the constants of Seeger's mass formula [36] and by using its temperature dependence given by Davidson *et.al.* [37]. The contributions of angular momentum deformations and orientations are included in Fragmentation potentials in order to account for recent developments in nuclear reaction dynamics. The advantage of this model is that it can be applied to all possible decay process like ER, Fusion-Fission, and QF etc. Another advantage of DCM over other statistical models is that the preformation probability (discussed in Chapter 2) accounts for much required structure properties of decaying nuclear systems. We have studied the decay of $^{202}Pb^*$, $^{176,182,188,196}Pt^*$ and $^{213,217}Fr^*$ nuclear systems formed in heavy ion reactions. Finally by employing $T=0$ and $\ell=0$ in DCM i.e. the PCM we have investigated the role of nuclear deformations and orientations in the ground-state exotic cluster decay process, the cluster radioactivity.

1.5 Organization of thesis

The thesis is organized as follows.

Chapter 2 gives the details of the theoretical model used for the present work. The Preformed Cluster Model (PCM) [22]- [25] and Dynamical Cluster-decay Model (DCM) [2, 4, 5], [15]- [18] of Gupta et al. have been explained in detail. Preformed

Cluster Model has been developed by adopting the Gamow's theory of α -decay. Here, instead of a square well potential, a more realistic nuclear potential, the nuclear proximity potential, is used and also a preformation probability P_0 is associated with each of the emitted cluster. PCM is applied to study the spontaneous cluster radioactivity process and DCM is used to study the decay of hot and rotating compound nucleus formed in heavy ion reactions, respectively. In DCM, besides the temperature and angular momentum effects in the decay of excited compound nuclei, the deformation and orientation effects of decay products are also taken care of. The DCM treats the CN decay of light particles LPs, intermediate mass fragments IMFs and heavy mass fragments HMFs or symmetric fission SF on equal footings, in contrast to the statistical models which use the Hauser-Feshbach (HF) analysis for LPs and binary fission for all other processes. The $\ell=0$, $T=0$ approximation reduces the DCM to PCM approach.

Chapter 3 deals with the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction at different center-of-mass energies, using the dynamical cluster-decay model (DCM) for spherical fragments [16]. The interesting feature of this study is that the three decay processes (ER, FF and QF) are quite comparable at low energies, ER being the most dominant, whereas at higher energies fusion-fission (FF) becomes most probable followed by ER and QF. The prediction of two fission windows, the symmetric fission (SF) and the near symmetric fission (nSF) whose contribution is more at lower incident energies, suggests the presence of a fine structure effect in the fusion-fission of $^{202}\text{Pb}^*$. The nSF window is shown to appear as "shoulders" in the otherwise Gaussian FF mass distribution, contributing to the non-compound-nucleus quasi-fission (QF) process. The nSF window (responsible for QF process)

is shown to be due to the presence of shell effects (magic shells) in the mass distributions, which is further supported by its absence (also, no QF decay channel) in the mass-fragmentation preformation yield calculations for the decay of compound nucleus $^{192}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction. The calculated ER, FF and QF cross-sections show excellent comparisons with the available experimental data [38].

In Chapter 4, we studied the decay of Pt isotopes $^{176,182,188,196}\text{Pt}^*$ formed by $^{64}\text{Ni} + ^{112}\text{Sn}$, $^{64}\text{Ni} + ^{118}\text{Sn}$, $^{64}\text{Ni} + ^{124}\text{Sn}$ and $^{132}\text{Sn} + ^{64}\text{Ni}$ reactions using the Dynamical Cluster-decay model (DCM) where the data for evaporation residue (ER) and fission cross-section are available both at near and below barrier energies [39]. Here, the calculations are done for the deformed fragments using quadrupole (β_2) deformations having optimal orientation for hot (compact) configuration. We observe that different isotopes of Pt^* display different decay patterns. With the increase in number of neutrons, i.e., with the increase of N/Z ratio of CN, the characteristics of the emitted light particles (the ER) change and the fission mass distribution changes from a symmetric to an asymmetric one. Specifically, for the neutron-rich, radioactive ^{132}Sn beam, the additional eight neutrons seems to be responsible for the neck-length parameter to be much smaller in $^{132}\text{Sn} + ^{64}\text{Ni}$ reaction, more so at higher energies, thereby indicating a different reaction-time scale for this reaction. On the other hand, for the fission process, as a result of the deformation and orientation effects, the lighter two systems $^{176,182}\text{Pt}^*$ are predominantly of the symmetric fission nature, whereas for the heavier two systems $^{188,196}\text{Pt}^*$ the asymmetric fission dominates. With increasing iso-spin ratio N/Z of CN, not only the reaction time scale changes but also a sub- or fine-structure of fission mass distributions is evident. Total fusion cross-sections (ER+fission+qf) calculated on DCM fit the data

nicely for all the four isotopes of Pt^* over a wide range of energies. Specifically, other model calculations, like the BPM, CCFULL and DC-TDHF, are available for the $^{132}Sn + ^{64}Ni \rightarrow ^{196}Pt$ reaction and the DCM results are better than these predictions [17], in particular at sub-barrier energies.

In Chapter 5, the decay of odd-mass nuclear systems $^{213}Fr^*$ (with $N=126$) and $^{217}Fr^*$ (with $N=130$) formed in $^{19}F + ^{194,198}Pt$ is studied using DCM by taking spherical and quadrupole deformed (β_2) considerations in an optimal orientations of hot (compact) configurations. Interestingly, the calculated fission distribution for $^{213}Fr^*$ and $^{217}Fr^*$ is symmetric for spherical case and asymmetric for β_2 deformation. The anomalous fission anisotropies measured for $N=126$ $^{213}Fr^*$ system, which are normal for the $N=130$ $^{217}Fr^*$ system, are considered to be associated with the neutron magic shell of the compound nucleus or a presence of nCN, qf component in the measured fission cross-sections. The near exact comparison between the calculated and experimental σ_{fiss} data (as well as the σ_{ER} data) for both the compound systems leaves no possibility of the quasi-fission component in the fission cross-section of either of the two systems. The β_2 deformed choice do not indicate the expected $N=126$ shell closure effect and hence don't resolve the measured anomaly in fission anisotropy for $^{213}Fr^*$ systems. It will be of interest to include "generalized deformation and orientation" in the decay process of these nuclei in order to further look for explicit role of $N=126$ in the decay of $^{213}Fr^*$ nucleus.

In Chapter 6, we have investigated the role of deformations and orientations of the decaying parent nucleus and of emitted fragment(s) in the ground state decay of daughter nuclei, using preformed cluster model (PCM) of Gupta and collaborators. The interesting feature of the study is that both Preformation Probability P_0 and

Penetration Probability P get modified with inclusion of deformation and orientation effects. We have studied the role of deformation and orientation [33, 34] for all the measured clusters, including the very recent experiments [40, 41] for the decay of ^{14}C and ^{15}N from ^{223}Ac and ^{34}Si from ^{238}U . It has been observed that β_2 alone is good enough to fit the experimental decay half-life times $T_{1/2}$ for majority of measured clusters. However higher multi-pole deformation effects seems essential for ^{14}C decay. It has been established through this study that deformation and orientation effects are extremely desirable, in addition to the shell and Q -value effects. However explicit role of higher multipole deformations need to be investigated specifically for ^{14}C cluster radioactivity.

Chapter 7, summarizes the overall work of the thesis. Brief notes regarding the significance of the work and conclusion drawn from it are explicitly given in this chapter. There is a definite scope for an extension of this work in future, discussed briefly in this chapter.

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Chapter 2

Methodology

2.1 Introduction

The reaction dynamics of hot and rotating, light as well as heavier compound systems at low energies have been studied extensively. The phenomenon of ground-state cluster decay of nuclei, cluster radioactivity, has also been investigated for the possible effects of oriented nuclei besides well established role of closed shells in the process. For the decay of excited compound systems, we have used the dynamical cluster-decay model (DCM) [1]- [9], including the deformations and orientations of nuclei. It is important to note that deformations and orientation effects of the reaction partners and decay products are explicitly included along with temperature and angular momentum contribution in this model. The ground state/spontaneous cluster decay of radioactive nuclei has been undertaken within the preformed cluster model (PCM) [10]- [18], again having deformations and orientation effects of the clusters as well as daughter nuclei included in it. Details of PCM and DCM are given in section 2.5 and 2.6, respectively, both of which stem from the Quantum

Mechanical Fragmentation Theory, (QMFT) [19]- [32] (section 2.2), which, in binary fragmentation, uses a collective mass transfer process.

In QMFT, the potential is calculated in macro-microscopic Strutinsky [33] method. The average two body potential successfully explains the cold and hot fusion reaction processes. The theory is based on the fact that the fragments are pre-born prior to the decay of the compound nucleus. The quantum mechanical preformation probability P_0 of the decaying fragments or clusters formed in the mother nucleus can be calculated by solving a stationary Schrödinger equation in mass fragmentation coordinate. Once the clusters are formed, their penetration probability P across the interaction barrier can be calculated by using the WKB approximation. The calculations of preformation probability P_0 and penetration probability P are discussed in section 2.3 and 2.4, respectively. The assault frequency, ν_0 , with which the preformed cluster bombard the barrier in ground state decay is discussed in section 2.5.

2.2 Quantum Mechanical Fragmentation Theory

QMFT [19]- [32], is a unified description of two body channels in both fusion and fission processes. Here the quantum mechanical concept of probability is utilized to investigate the role of shell effects in the fusion, fission and cluster radioactivity. In *QMFT*, nuclear dynamics is explained by the potential energy surfaces and the mass parameters defining the kinetic energy of the system while the static properties of nuclear system are determined by the potential energy only. The *QMFT* is worked out in terms of the following collective coordinates:

1. Relative separation coordinate R between the two nuclei or, in general, two fragments (or, equivalently, the length parameter $\lambda = L/2R_0$, with L as the length of the nucleus and R_0 as the radius of an equivalent spherical nucleus).
2. Mass and charge fragmentation co-ordinates [19], [20], [31] defined by the mass and charge-asymmetry coordinates as

$$\eta = \frac{A_1 - A_2}{A}; \quad \eta_Z = \frac{Z_1 - Z_2}{Z} \quad (2.1)$$

Similarly, the neutron asymmetry coordinate [20]

$$\eta_N = \frac{N_1 - N_2}{N}, \quad (2.2)$$

can also be used, but it is sufficient to treat only two of them as dynamical co-ordinates since they are related as

$$\eta = \frac{Z}{A}\eta_Z + \frac{N}{A}\eta_N \quad (2.3)$$

Here $A = A_1 + A_2$, $Z = Z_1 + Z_2$ and $N = N_1 + N_2$. A_i , Z_i and N_i ($i = 1, 2$) are respectively the mass number, the charge number and the neutron number of two fragments. A , Z and N are respectively the mass number, charge number and neutron number of the compound system. The limiting values of η are $0 \leq |\eta| \leq 1$ and thus allows a unified description of a few-nucleon or multi-nucleon (a cluster) transfer, a large-mass transfer, the complete fusion ($|\eta| = 1$) of nuclei and the symmetric ($\eta = 0$), asymmetric and super-asymmetric fission of a nucleus or compound nucleus. The η_Z coordinate gives the associated

charge distribution effects.

3. The deformation co-ordinates $\beta_{\lambda i}$ ($\lambda=2,3,4\dots$ and $i=1,2$) of the colliding nuclei or fragments.
4. The orientation degrees of freedom θ_i ($i=1,2$) of the deformed nuclei (see Fig. 1.3).
5. Azimuthal angle ϕ between the principal planes of the two colliding nuclei.
6. Neck parameter ε , defined by the ratio $\varepsilon = E_0/E'$ for the interaction region ($R < R_1 + R_2$, R_i ($i=1, 2$) is the radius of the two nuclei);
where E_0 is the actual height of the barrier and E' is the fixed barrier of the two center oscillator. $\varepsilon = 0$ represents a broad neck formation, whereas $\varepsilon = 1$ gives that the neck is fully squeezed in, corresponding to the asymptotic region ($R > R_1 + R_2$).

In terms of these collective coordinates and their velocities, the collective Hamiltonian can be written as

$$H = K(\mathbf{R}, \beta, \varepsilon, \eta, \eta_Z; \dot{\mathbf{R}}, \dot{\beta}, \dot{\varepsilon}, \dot{\eta}, \dot{\eta}_Z) + V(\mathbf{R}, \beta, \varepsilon, \eta, \eta_Z). \quad (2.4)$$

Here β is taken as $\beta_{\lambda 1}$ and $\beta_{\lambda 2}$ with $\lambda=2,3,4\dots$, K refers to the kinetic energy and V to the collective potential energy. For fixed β and ε , the potential $V(\eta; \eta_Z; \mathbf{R})$, minimized in the η_Z co-ordinate gives the Schrödinger wave equation, in terms of mass parameters and relative separation $\mathbf{R}$ co-ordinates, as

$$H(\eta, R)\psi(\eta, R) = E(\eta, R)\psi(\eta, R) \quad (2.5)$$

with the Hamiltonian,

$$H(\eta, R) = K(\eta) + K(R) + K(\eta, R) + V(\eta) + V(R) + V(\eta, R) \quad (2.6)$$

The mass parameters B_{ij} , defining the kinetic energy term K in the above Eqs. (2.4) and (2.6) are either the consistently calculated cranking masses using the Asymmetric Two-Center Shell Model (*ATCSM*) or the classical hydrodynamical masses, which are shown to have good agreement with microscopic cranking calculations.

The coupling term of the kinetic energy $K(\eta, R)$, proportional to $\frac{\partial^2}{\partial \eta \partial R}$, is neglected here, since the coupled cranking masses are very small [19, 20] ($B_{R\eta} \ll (B_{RR}B_{\eta\eta})^{1/2}$ and $B_{R\eta Z} \ll (B_{RR}B_{\eta Z\eta Z})^{1/2}$). Same is true for the coupling term of potential energy $V(\eta, R)$.

Therefore, in a decoupled approximation [32], the Schrödinger equation (2.5) can be solved for which the Hamiltonian takes the form:

$$H = -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} - \frac{\hbar^2}{2\sqrt{B_{RR}}} \frac{\partial}{\partial R} \frac{1}{\sqrt{B_{RR}}} \frac{\partial}{\partial R} + V(\eta) + V(R). \quad (2.7)$$

For decoupled Hamiltonian (2.7), Schrödinger wave equation (2.5) can be separated for the two co-ordinates η and R as follows,

$$\left[-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V(\eta) \right] \psi^\nu(\eta) = E_\eta^\nu \psi^\nu(\eta) \quad (2.8)$$

and

$$\left[-\frac{\hbar^2}{2\sqrt{B_{RR}}} \frac{\partial}{\partial R} \frac{1}{\sqrt{B_{RR}}} \frac{\partial}{\partial R} + V(R) \right] \psi^\nu(R) = E_R^\nu \psi^\nu(R) \quad (2.9)$$

with

$$\psi(\eta, R) = \psi(\eta)\psi(R) \quad (2.10)$$

and

$$E = E_\eta + E_R \quad (2.11)$$

The states $\psi^\nu(\eta)$ are the vibrational states in the potential $V(\eta)$ and are labelled by the quantum numbers $\nu = 0, 1, 2, \dots$

In the following subsections, we first discuss the various terms of Schrödinger wave equations (2.8) and (2.9) and then give the solution of Eq. (2.8) for the determination of preformation probability $P_0 \propto |\psi^0(\eta)|^2$.

2.2.1 The Scattering Potential $V(R)$

For a fixed η i.e for a given target projectile (A_1, A_2) combination, the scattering potential $V(R)$ in Eq. (2.9) is defined as the sum of the temperature as well as deformations and orientations dependent Coulomb potential, proximity potential and angular momentum dependent potential, i.e.

$$\begin{aligned} V(R, \ell, T) = & V_c(R, Z_i, \beta_{\lambda i}, \theta_i, \phi, T) + V_p(R, A_i, \beta_{\lambda i}, \theta_i, \phi, T) \\ & + V_\ell(R, A_i, \beta_{\lambda i}, \theta_i, \phi, T) \end{aligned} \quad (2.12)$$

For spherical-plus-deformed nuclear collisions, only one orientation angle θ is enough, referring to the rotationally-symmetric deformed nucleus ($\phi=0^\circ$ for coplanar nuclei).

2.2.2 The Fragmentation potential $V(\eta)$

The temperature dependent collective potential energy or the fragmentation potential $V(\eta, R, T)$, appearing in equation (2.8), is calculated as,

$$\begin{aligned} V(\eta, R, \ell, T) = & - \sum_{i=1}^2 B_i(A_i, Z_i, \beta_{\lambda i}, T) + V_c(R, Z_i, \beta_{\lambda i}, \theta_i, \phi, T) \\ & + V_p(R, A_i, \beta_{\lambda i}, \theta_i, \phi, T) + V_\ell(R, A_i, \beta_{\lambda i}, \theta_i, \phi, T) \end{aligned} \quad (2.13)$$

The fragmentation potential $V(\eta)$ is calculated at a fixed distance $R = R_1 + R_2 + \delta R$, for consideration of deformed and oriented reaction product, with

$$R_i(\alpha_i, T) = R_{0i}(T) \left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i) \right], \quad (2.14)$$

and

$$R_{0i}(T) = [1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}](1 + 0.0007T^2). \quad (2.15)$$

Here $\lambda = 2, 3, 4..$ and α_i is an angle that the radius vector R_i of the colliding nuclei makes with the symmetry axis (see Fig. 1.3), measured clockwise.

2.2.3 Temperature dependent binding energies

The binding energy B of a nucleus at temperature T has been defined, within the Strutinsky renormalization procedure [33], as the sum of liquid drop energy $V_{LDM}(T)$ and shell correction $\delta U(T)$ i.e

$$B_i(A_i, Z_i, \beta_{\lambda i}, T) = \sum_{i=1}^2 V_{LDM}(A_i, Z_i, T) + \sum_{i=1}^2 \delta U \exp \left(-\frac{T^2}{T_0^2} \right) \quad (2.16)$$

2.2.4 Liquid drop energies and their temperature dependence

The T dependent liquid drop part of the binding energy $V_{LDM}(T)$, is taken from Davidson *et al.* [34], based on the semi-empirical mass formula of Seeger [35], as

$$\begin{aligned}
 V_{LDM}(A, Z, T) = & \alpha(T)A + \beta(T)A^{\frac{2}{3}} + \left(\gamma(T) - \frac{\eta(T)}{A^{\frac{1}{3}}} \right) \left(\frac{I^2 + 2 |I|}{A} \right) \\
 & + \frac{Z^2}{R_0(T)A^{\frac{1}{3}}} \left(1 - \frac{0.7636}{Z^{\frac{2}{3}}} - \frac{2.29}{[R_0(T)A^{\frac{1}{3}}]^2} \right) + \delta(T) \frac{f(Z, A)}{A^{\frac{3}{4}}},
 \end{aligned} \tag{2.17}$$

where

$$I = a_a(Z - N), \quad a_a = 1.0,$$

and, respectively, for even-even, even-odd, and odd-odd nuclei,

$$f(Z, A) = (-1, 0, 1).$$

For $T = 0$, Seeger [35] obtained the constants, by fitting all even-even nuclei and 488 odd- A nuclei available at that time, as

$$\alpha(0) = -16.11 \text{ MeV}, \quad \beta(0) = 20.21 \text{ MeV},$$

$$\gamma(0) = 20.65 \text{ MeV}, \quad \eta(0) = 48.00 \text{ MeV},$$

with the pairing energy term

$$\delta(0) = 33.0\text{MeV},$$

from Ref. [38]. Evidently, these constants need to be re-fitted since a large amount of both experimental and theoretical data has become available [36, 37] particularly for neutron-rich nuclei. The newly fitted constants give binding energy within < 1.5 MeV of experiments [8].

The T -dependent constants in Eq. (2.17) were obtained numerically by Davidson *et al.* [34] for the available experimental information on excited states of 313 nuclei in the mass region $22 \leq A \leq 250$ by determining the partition function $\mathcal{Z}(A, Z, T)$ of each nucleus in the canonical ensemble and making a least squares fit of the excitation energy

$$E_{ex}(A, Z, T) = V_{LDM}(A, Z, T) - V_{LDM}(A, Z, 0)$$

to the ensemble average

$$E_{ex}(A, Z, T) = T^2 \frac{\partial}{\partial T} \ln \mathcal{Z}(A, Z, T).$$

The $\alpha(T)$, $\beta(T)$, $\gamma(T)$, $\eta(T)$ and $\delta(T)$ thus obtained are shown in Figure 3.1 from Ref. [34] for $T \leq 4 \text{ MeV}$, extrapolated linearly for higher temperatures. For the bulk constant $\alpha(T)$, instead, an empirically fitted expression to a Fermi gas model is used, as

$$\alpha(T) = \alpha(0) + \frac{T^2}{15}.$$

Also, the $\delta(T)$ is constrained to be positive definite at all temperatures, with $\delta(T > 2\text{MeV}) = 0$. Finally, the analytical form used for $R_0(T)$ is

$$R_0(T) = 1.07(1 + 0.01T)$$

instead of Eq. (2.15).

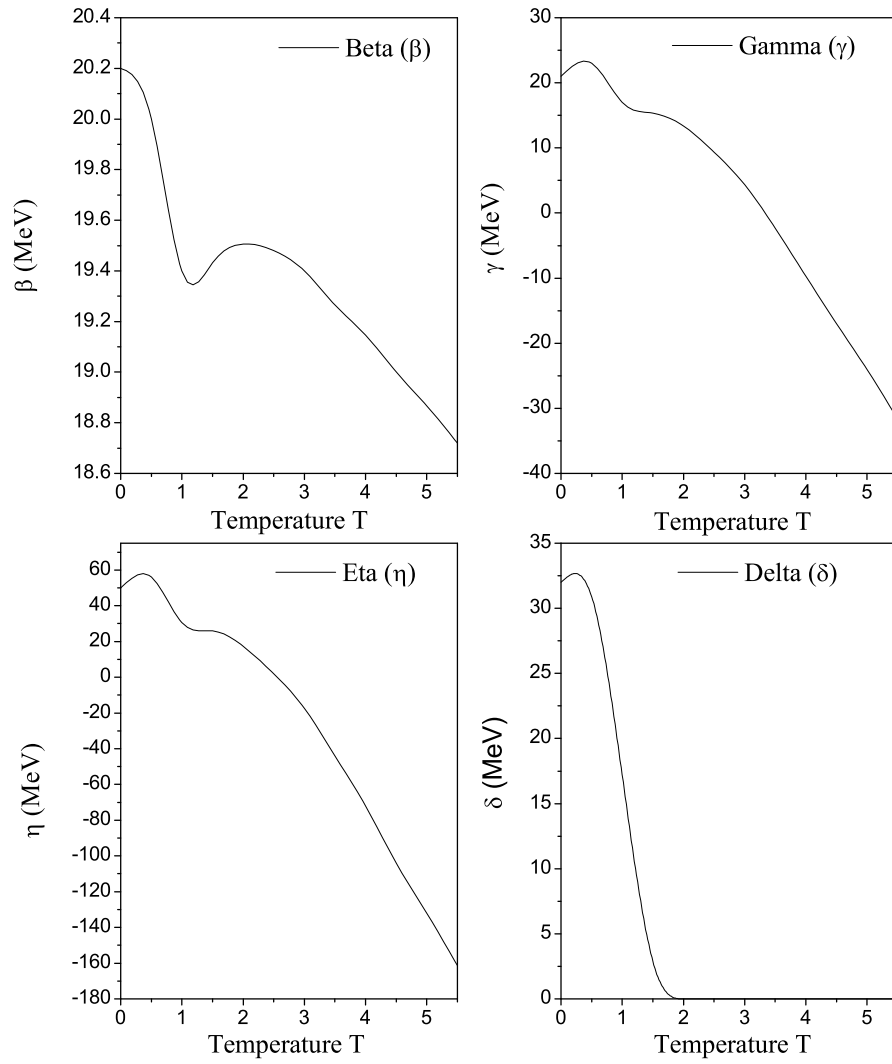


Figure 2.1 The coefficients of the semiempirical mass formula (Eq. 2.17), $\alpha(\text{MeV})$, $\beta(\text{MeV})$, $\gamma(\text{MeV})$, $\eta(\text{MeV})$ and $\delta(\text{MeV})$ as a function of the temperature $T(\text{MeV})$.

2.2.5 Shell corrections and their temperature dependence

For the shell corrections δU in Eq. (2.16), since there is no microscopic shell model known that gives the shell corrections for light nuclei, we use the empirical formula of Myers and Swiatecki [39]. For spherical shapes,

$$\delta U = C \left[\frac{F(N) + F(Z)}{(A/2)^{\frac{2}{3}}} - cA^{\frac{1}{3}} \right] \quad (2.18)$$

where

$$F(X) = \frac{3}{5} \left(\frac{M_i^{\frac{5}{3}} - M_{i-1}^{\frac{5}{3}}}{M_i - M_{i-1}} \right) (X - M_{i-1}) - \frac{3}{5} \left(X^{\frac{5}{3}} - M_{i-1}^{\frac{5}{3}} \right) \quad (2.19)$$

with $X = N$ or Z , $M_{i-1} < X < M_i$ and M_i as the magic numbers 2, 8, 14 (or 20), 28, 50, 82, 126 and 184 for both neutrons and protons. The constants $C = 5.8$ MeV and $c = 0.26$. In this work, we refer to the use of magic number 20 as *MS20* parameterization. The temperature dependence of shell corrections δU is obtained as given in equation 2.16, decreasing exponentially with $T_0=1.5$ MeV.

At higher excitation energies the shell corrections vanish completely and only the liquid drop part of energy is present. The shell corrections play an important role in determining or empirical fitting of nuclear masses, because the nuclear masses calculated by using the smooth liquid drop formula show large deviations with respect to the experimental masses. It means that in the experimental masses there exist deep minima at specific neutron and/or proton numbers indicating the presence of shell structure, the so-called magic numbers in nuclei. This characteristic behavior cannot be reproduced by the liquid drop part alone, which means that the introduction of microscopic shell correction in the mass formula is essential. Thus, shell corrections accounts for the removal of deviation from the liquid drop calculations

(uniform distribution of nucleons), and are defined, within Strutinsky [33] method as

$$\delta U = U - \tilde{U} \quad (2.20)$$

where, $U = \sum_{\nu} E_{\nu} 2n_{\nu}$ is the sum over all occupied single particle states and

$$\tilde{U} = 2 \int_{-\infty}^{\tilde{\lambda}} E \tilde{g}(E) dE. \quad (2.21)$$

is the average energy for uniform distribution. In general, the microscopic shell correction, together with the liquid drop part, gives a proper description of the binding energy of the nucleus.

The nuclear temperature T (in MeV) is related to the excitation energy E_{CN}^* of the compound nucleus, through a semi-empirical statistical relation as:

$$E_{CN}^* = \frac{1}{a} A T^2 - T \quad (MeV). \quad (2.22)$$

where $a = 9-11$ depending on the mass of the compound nucleus.

2.2.6 The Proximity Potential for deformed, oriented, coplanar nuclei

When two surfaces approach each other within a small distance of less than $\sim 2fm$, comparable with the surface thickness of interacting nuclei, or when a nucleus is at the verge of dividing into two fragments, then the two surfaces actually face each other across a small gap or crevice. In both cases, the surface energy term alone could not give rise to the strong attraction that is observed when the two surfaces

are brought in close proximity. Such additional attractive forces are called proximity forces and the additional potential due to these forces is called the nuclear proximity potential. Blocki *et al.* [40] have reanalyzed and extended a theorem, originally due to Deryagin [41], according to which the force between two gently curved surfaces in close proximity is proportional to the interaction potential per unit area between the two flat surfaces. The proximity potential for hot deformed nuclei is given as

$$V_p(A_i, \beta_{\lambda i}, \theta_i, T) = 4\pi \bar{R}(T) \gamma b(T) \Phi(s_0(T)). \quad (2.23)$$

$\Phi(s_0)$ is the universal function, independent of the shapes of nuclei or the geometry of nuclear system, but depends on the minimum separation distance s_0 ,

$$\Phi(s_0) = \begin{cases} -\frac{1}{2}(s_0 - 2.54)^2 - 0.0852(s_0 - 2.54)^3 \\ -3.437 \exp(-\frac{s_0}{0.75}) \end{cases} \quad (2.24)$$

respectively, for $s_0 \leq 1.2511$ and $s_0 \geq 1.2511$. Here, s_0 is defined in units of b , i.e. s_0 is s_0/b . This function is defined for negative (the overlap region), zero (touching configuration) and positive values of s_0 . s_0 , distance of closest approach defined in Fig. 1.4, depends on deformations and orientations of reactants/products (explained later in this section). Where b is the diffuseness of the nuclear surface and is given by

$$b = \left[\pi/2\sqrt{3} \ln 9 \right]_{t_{10-90}}$$

where t_{10-90} is the thickness of the surface in which the density profile changes from 90% to 10%. The value of $b \sim 1$ fm. However, temperature dependent b is given as

$$b(T) = 0.99(1 + 0.009T^2) \quad (2.25)$$

The γ is the specific nuclear surface tension given by

$$\gamma = 0.9517 \left[1 - 1.7826 \left(\frac{N - Z}{A} \right)^2 \right] \text{MeV fm}^{-2} \quad (2.26)$$

$\bar{R}$ is the mean curvature radius of the reaction partners and is described in the following for deformed and oriented nuclei.

Fig. 1.4 shows a schematic configuration of two (equal/ unequal) axially symmetric deformed, oriented nuclei, lying in the same plane ($\phi = 0^\circ$), for various θ_1 and θ_2 values in the range 0° to 180° . θ_i is the angle of orientation, defined as an angle between the symmetry axis and the axis of collision, with its rotation measured in anti-clockwise direction from the axis of collision. α_i is an angle between the symmetric axis and the radius vector $R_i(\alpha_i)$ of the colliding nuclei, measured in clockwise direction from the symmetry axis of the nucleus.

For the axially symmetric shapes, the nuclear radius parameter (to all higher multipole orders $\lambda=2,3,4,\dots$) is given by Eqs. (2.14) and (2.15). In terms of the radii of curvature R_{i1} and R_{i2} in the principal planes of curvature of each of the two nuclei ($i=1,2$) at the points of closest approach (defining s_0 in Fig. 1.4), the mean

curvature radius $\bar{R}$ for deformed, oriented nuclei is given by

$$\begin{aligned} \frac{1}{\bar{R}^2} &= \frac{1}{R_{11}R_{12}} + \frac{1}{R_{21}R_{22}} + \left[\frac{1}{R_{11}R_{21}} + \frac{1}{R_{12}R_{22}} \right] \sin^2 \phi \\ &+ \left[\frac{1}{R_{11}R_{22}} + \frac{1}{R_{21}R_{12}} \right] \cos^2 \phi. \end{aligned} \quad (2.27)$$

Here, ϕ is the azimuthal angle between the principal planes of curvature of two nuclei (for co-planar nuclei $\phi=0^0$). The four principal radii of curvature are

$$\begin{aligned} R_{i1}(\alpha_i) &= \frac{[R_i^2(\alpha_i) + R_i'^2(\alpha_i)]^{3/2}}{R_i^2(\alpha_i) + 2R_i'^2(\alpha_i) - R_i(\alpha_i)R_i''(\alpha_i)} \\ R_{i2}(\alpha_i) &= \frac{R_i(\alpha_i)\sin\alpha_i}{\cos(\pi/2 - \alpha_i - \delta_i)}. \end{aligned} \quad (2.28)$$

where, $R_i'(\alpha_i)$ and $R_i''(\alpha_i)$ are the first and second order derivatives of $R_i(\alpha_i)$ with respect to α_i , respectively. For the derivation of the radius of curvature R_{i1} , see [42], and it follows from Fig. 2.2, and Ref. [43], that $R_{i2} = h/\cos\omega_i$, with $h = R_i(\alpha_i)\sin\alpha_i$ and $\omega_i = \pi/2 - \alpha_i - \delta_i$. Also, for $\mathbf{n}$ to be a normal vector

$$\tan\delta_i = -\frac{R_i'(\alpha_i)}{R_i(\alpha_i)}. \quad (2.29)$$

Note that $R_{i1}(\alpha_i) = R_{i2}(\alpha_i)$, respectively, for $\alpha_1 = 0^0$ or 180^0 and $\alpha_2 = 180^0$ or 360^0 .

For a configuration of deformed, oriented nuclei, the minimum distance s_0 (Fig. 1.4)

in Eq. (2.24) is

$$s_0 = R - X_1 - X_2 \quad (2.30)$$

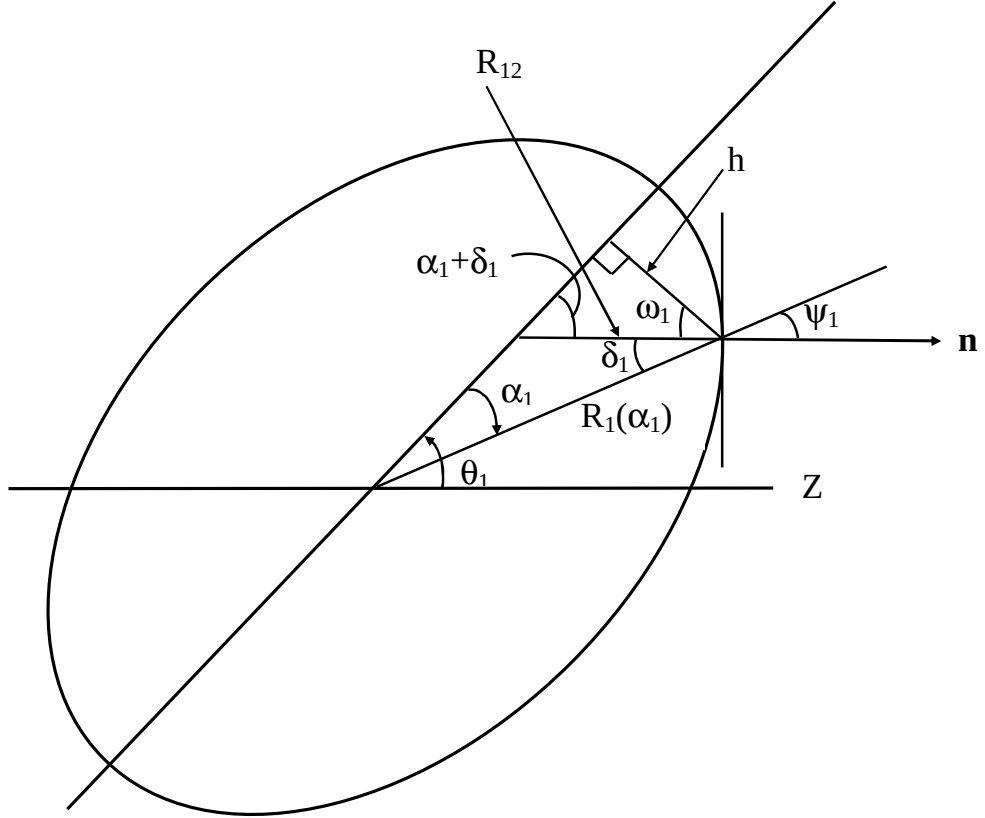


Figure 2.2 An axially symmetric (quadrupole) deformed and oriented nucleus, showing the nuclear radius parameter $R_1(\alpha_1)$ and the geometry associated with the principal radius of curvature $R_{12}(\alpha_1)$.

with the projections X_i along the collision Z-axis given as

$$\begin{aligned} X_1 &= R_1(\alpha_1) \cos(\theta_1 - \alpha_1) \\ X_2 &= R_2(\alpha_2) \cos(180 + \theta_2 - \alpha_2) \end{aligned} \quad (2.31)$$

with the minimization conditions on s_0 ,

$$\frac{\partial s_0}{\partial \alpha_1} = \frac{\partial s_0}{\partial \alpha_2} = 0, \quad (2.32)$$

resulting in

$$\begin{aligned}\tan(\theta_1 - \alpha_1) &= -\frac{R'_1(\alpha_1)}{R_1(\alpha_1)} \\ \tan(180 + \theta_2 - \alpha_2) &= -\frac{R'_2(\alpha_2)}{R_2(\alpha_2)}.\end{aligned}\tag{2.33}$$

Comparing Eqs. (2.30) and (2.34), we get

$$\begin{aligned}\delta_1 &= \theta_1 - \alpha_1 \\ \delta_2 &= 180 + \theta_2 - \alpha_2,\end{aligned}\tag{2.34}$$

to be used in Eq. (2.28).

Thus, for the given θ_1 and θ_2 , X_1 and X_2 are obtained for the angles α_1 and α_2 satisfying the minimization conditions Eq. (2.33). In a detailed study [44], based upon QMFT by Gupta and collaborators, the optimum orientations are given for "cold, non-compact" or "hot, compact" fusion configurations corresponding to largest interaction radius and lowest barrier and smallest interaction radius and highest barrier, respectively (the details can be seen in Table 1 of [44]). These optimum orientations have been used in the present study for cluster radioactive decay and for the decay of excited CN.

Note that the conditions of Eq. (2.33) refer to perpendiculars (normal vectors) at the points P_1 and P_2 . In other words, if the distance s_0 were to be shortest, the perpendicular conditions, Eq. (2.33), must be used which would apparently give equations Eq. (2.31) for X_i . Eq. (2.23) is valid for zero (touching configuration) and positive values of s_0 , but is also used for negative s_0 . As the two nuclei overlap

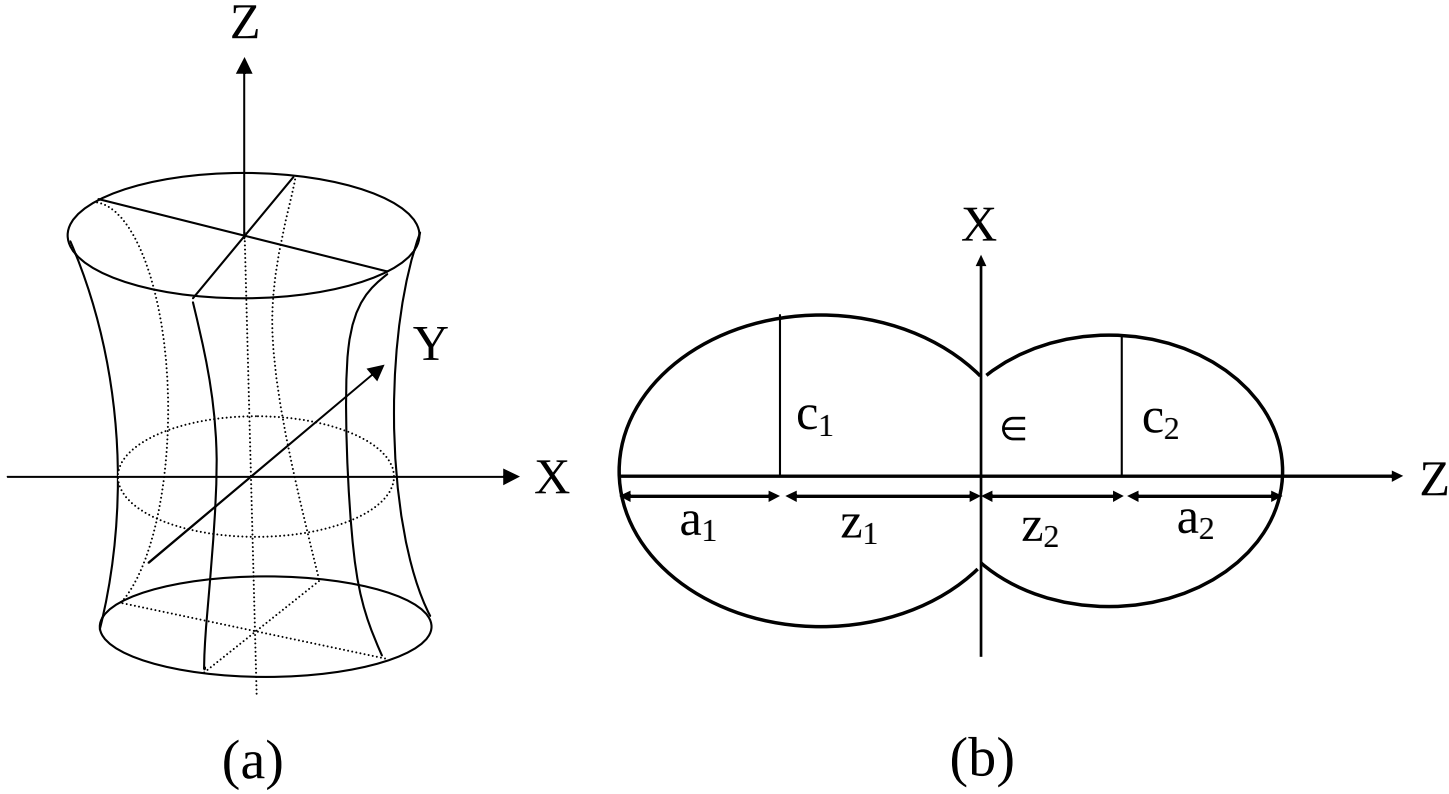


Figure 2.3 (a) Schematic representation of a hyperboloid of revolution in one sheet. (b) Sample nuclear shape formed in two center shell model.

($s_0 < 0$), a crevice is formed and, in an adiabatic approximation, the system adjusts its shape parameters such that the two colliding nuclei form a single indented body in the form of a single hyperboloid of one sheet with a hyperboloidal crevice, as shown in Fig. 2.3 (a). For such a necked system, shown in Fig. 2.3(b), following Blocki *et al.* [40], the proximity potential is obtained by Gupta and collaborators [15], [45] as

$$V_P(s_0) = \pi\gamma b^2 \Phi_1(s_0 = 0) \frac{(c_1^2 + c_2^2 - 2\epsilon^2)}{(z_1^2 + z_2^2)} \quad (2.35)$$

where $\Phi_1(s_0 = 0) = -2.0306$ is the first moment of the universal function Φ at $s_0 = 0$, and c_i , z_i and ϵ are the shape parameters in Fig. 2.3 (b). Apparently, for two equal

nuclei, $z_1 = z_2$ and $c_1 = c_2$.

2.2.7 The Coulomb potential

Coulomb potential describes the force of repulsion between two interacting nuclei due to their charges. It acts along the line joining the two nuclei. The Coulomb potential for two interacting hot, deformed and oriented nuclei is given as

$$V_c(Z_i, \beta_{\lambda i}, \theta_i, T) = \frac{Z_1 Z_2 e^2}{R(T)} + 3Z_1 Z_2 e^2 \sum_{\lambda, i=1,2} \frac{R_i^\lambda(\alpha_i, T)}{(2\lambda + 1)R(T)^{\lambda+1}} Y_\lambda^{(0)}(\theta_i) \left[\beta_{\lambda i} + \frac{4}{7} \beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i) \right], \quad (2.36)$$

with R_i from Eq. (2.14). $Y_\lambda^{(0)}(\theta_i)$ are the spherical harmonics function.

2.2.8 Rotational Energy due to angular momentum

The rotational motion gives an additional energy due to the angular momentum ℓ , defined as

$$V_\ell(R, A_i, \beta_{\lambda i}, \theta_i, T) = \frac{\hbar^2 \ell(\ell + 1)}{2I_s(T)} \quad (2.37)$$

with $I(T) = \mu R^2$, is the non-sticking limit of moment of inertia with $\mu = \frac{A_1 A_2}{A_1 + A_2} m$ as the reduced mass, m is the nucleon mass. In the complete sticking limit, the moment of inertia I is given as,

$$I_s(T) = \mu R^2 + \frac{2}{5} A_1 m R_1^2(\alpha_1, T) + \frac{2}{5} A_2 m R_2^2(\alpha_2, T). \quad (2.38)$$

with R_i from Eq. (2.14). For the relative separation of interest here, we use the sticking limit. However it is relevant to mention here that value of angular mo-

momentum extracted experimentally, is based on the moment of inertia in non-sticking limit (i.e. $I_{NS} = \mu R^2$) [46]. It means that fragment emission is punctual. In our recent study we find that sticking limit is more appropriate for the proximity potential (nuclear surface ≤ 2 fm apart) which consequently results in to large limiting value of angular momentum [8].

2.2.9 Classical Hydrodynamical Mass Parameters

The kinetic energy part of the Hamiltonian in Eq. (2.8) enters through the mass parameters. We use here the classical mass parameters of Kröger and Scheid [47]. The model of Kröger and Scheid is based on the hydrodynamical flow, as shown in Fig. 2.4. This model gives a simple analytical expression, whose predictions are shown to compare nicely with the microscopic cranking model calculations. For the $B_{\eta\eta}$ mass we get,

$$B_{\eta\eta} = \frac{AmR^2}{4} \left[\frac{v_t(1+\gamma)}{v_c(1+\delta^2)} - 1 \right] \quad (2.39)$$

with

$$\gamma = \frac{R_c}{2R} \left[\frac{1}{1+\cos\vartheta_1} \left(1 - \frac{R_c}{R_1} \right) + \frac{1}{1+\cos\vartheta_2} \left(1 - \frac{R_c}{R_2} \right) \right] \quad (2.40)$$

$$\delta = \frac{1}{2R} [(1-\cos\vartheta_1)(R_1-R_c) + (1-\cos\vartheta_2)(R_2-R_c)] \quad (2.41)$$

$$v_c = \pi R_c^2 R \quad (2.42)$$

and $v_t = v_1 + v_2$, is the total conserved volume. The angles ϑ_1 and ϑ_2 and geometry of the model are shown in Fig. 2.4. For $\vartheta_1 = \vartheta_2 = 0$, $\delta = 0$ which corresponds

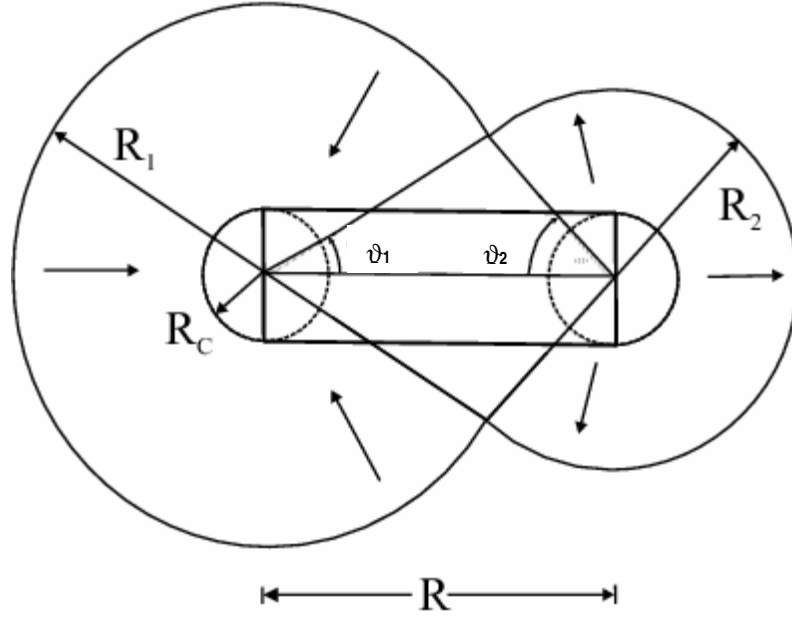


Figure 2.4 The geometry of the classical hydrodynamical model of Kröger and Scheid for calculating the mass parameter $B_{\eta\eta}$.

to two touching spheres. $R_c (\neq 0)$ is the radius of a cylinder of length R , having a homogeneous flow in it; whose existence is assumed for the mass transfer between the two spherical fragments. We have generalized this expression for deformed nuclei by using the radii R_1 and R_2 for hot deformed nuclei, given by Eq. (2.14).

2.3 Preformation Probability P_0

Once the Hamiltonian Eq. (2.7) is established, the Schrödinger equation in mass fragmentation co-ordinate η can be solved. On solving Eq. (2.8) numerically, $|\psi^\nu(\eta)|^2$ gives the probability P_0 of finding the mass fragmentation η at a fixed

R on the decay path.

$$P_0(A_2) \propto |\psi^\nu(A_2)|^2 \quad (2.43)$$

For fission studies, like the spontaneous fission and fission through the barrier, the motion in R at the saddle point is adiabatically slow as compared to the η motion. Therefore, the potential is minimized in the neck ε and deformation coordinates β_1 and β_2 at each R and η values. Starting from the nuclear ground state in spontaneous fission or cluster decay, and to have complete adiabaticity, only the lowest vibrational state $\nu = 0$ is occupied. Then, the mass (or charge) distribution yield, proportional to the probability $|\psi^{(0)}(\eta)|^2$ (or $|\psi^{(0)}(\eta_Z)|^2$) of finding a certain mass (or charge) fragmentation η (or η_Z) at a position R on the decay path, when scaled to, say, mass A_2 of one of the fragments ($d\eta = \frac{2}{A}$) is given by:

$$P_0(A_2) = |\psi_R^{(0)}(A_2)|^2 \frac{2}{A} \sqrt{B_{\eta\eta}(A_2)}. \quad (2.44)$$

However, if the system is excited or we allow interaction between various degrees of freedom, higher values of ν would also contribute. These enter via the excitation of higher vibrational states, and through the temperature dependent potential V and masses B_{ij} .

The effect of adding temperature on potential V and masses B_{ij} is to reduce the shell effects in them, resulting finally in the liquid drop potential V_{LDM} and smoothed (averaged) masses $\bar{B}_{ij}$ for the systems to be very hot. Apparently, cold fission means taking both the potential V and masses B_{ij} with full shell effects included in them and hot fission means using the V_{LDM} and smoothed (averaged) masses $\bar{B}_{ij}$. The possible consequence of such excitations are included here by assuming a Boltzmann

like occupation of excited states

$$|\psi(\eta)|^2 = \sum_{\nu=0}^{\infty} |\psi^{\nu}(\eta)|^2 \exp\left(-\frac{E_{\eta}^{\nu}}{T}\right) \quad (2.45)$$

Note that we are dealing here with a directly measurable quantity, the mass (or charge) asymmetry, which works dynamically as mass (or charge) transfer coordinate. Thus, the calculated yields $P_0(A_i)$ (or $P_0(Z_i)$) are directly comparable with experiments. It may be stressed that there is no free parameter in these calculations. The nuclear shape, once minimized in the neck ε and deformation coordinates β_1 and β_2 at a given R ($\approx R_{saddle}$), remains fixed for both the mass and charge distributions of fission or decay fragments.

For the competing, non-compound, quasi-fission (qf) decay channel, the incoming nuclei keep their identity, and hence the preformation factor $P_0=1$ for η_i in case of qf.

2.4 Penetration Probability P

For R -motion, instead of solving the Schrödinger Eq.(2.9), Gupta and collaborators used the WKB approximation to calculate the penetration probability P . For each η -value, the potential $V(R)$ for $R \geq R_t$ is calculated by using Eq.(2.12) and for $R < R_t$ it is parameterized simply as a polynomial of degree two in R , so that

$$V(R) = \begin{cases} a_1 R + a_2 R^2 & \text{for } R_0 \leq R \leq R_t \\ V_c + V_p + V_{\ell} & \text{for } R \geq R_t \end{cases} \quad (2.46)$$

A typical scattering potential, for $^{231}\text{Pa} \rightarrow ^{24}\text{Ne} + ^{207}\text{Tl}$ is shown in Fig. 2.5. This

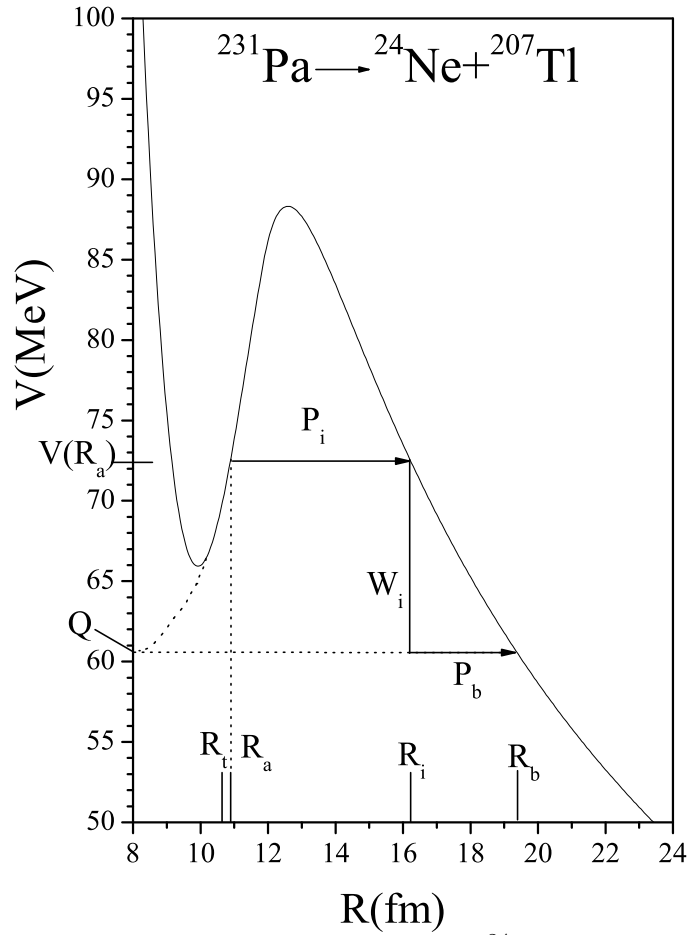


Figure 2.5 The scattering potentials for the ^{24}Ne cluster decay of parent nucleus ^{232}U , i.e., $^{231}\text{Pa} \rightarrow ^{24}\text{Ne} + ^{207}\text{Tl}$, for ^{24}Ne considered as a deformed nucleus with "optimum" cold orientation angles θ_i^{opt} with characteristic quantities marked in it.

is calculated by using Eq. (2.12) for the case of $\ell=0$. The path of the penetration and the related quantities are also shown in Fig. 2.5.

The constants a_i ($i = 1, 2$) occurring in the polynomial, are determined by using the following boundary conditions.

1. At $R = R_0$, $V(R) = Q$
2. At $R = R_t$, $V(R) = V(R_t)$

In order to avoid the use of undetermined part of the potential, i.e., $V(R_0 \leq R \leq R_t)$,

the first (inner) turning point R_a is chosen at the touching configuration, $R_a = R_t$, and the outer turning point is taken at R_b to give the Q -value of the reaction, i.e., $V(R_b) = Q$. This means that the transmission probability P consists of three contributions

1. The penetrability P_i from R_t to R_i ,
2. the (inner) de-excitation probability W_i at R_i and
3. the penetrability P_b from R_i to R_b

giving the penetration probability as

$$P = P_i W_i P_b. \quad (2.47)$$

The shifting of first turning point from R_t to R_0 gives the penetrability calculations similar to Shi and Swiatecki [48] for spherical nuclei, which is known not to fit the experimental data without the adjustment of assault frequency. Following the excitation model of M. Greiner and W. Scheid [49], the de-excitation probability W_i is given as

$$W_i = \exp(-bE_i) \quad (2.48)$$

This means that the de-excitation process is restricted to only a single transition. If the parameter b were allowed to depend on R_i , it should then become a process of multiple de-excitation and proceed as step-like process. For a heavy cluster decay into the excited states of the daughter nucleus, the $b = 0$ is assumed [49], which means

$$W_i = 1, \quad (2.49)$$

so that,

$$P = P_i P_b, \quad (2.50)$$

where P_i and P_b are calculated by using WKB approximation, as

$$P_i = \exp \left[-\frac{2}{\hbar} \int_{R_a}^{R_i} \{2\mu[V(R) - V(R_i)]\}^{1/2} dR \right] \quad (2.51)$$

and

$$P_b = \exp \left[-\frac{2}{\hbar} \int_{R_i}^{R_b} \{2\mu[V(R) - Q]\}^{1/2} dR \right]. \quad (2.52)$$

Here R_a and R_b are, respectively, the first and second turning points. This means that the tunnelling begins at $R = R_a$ and terminates at $R = R_b$, with $V(R_b) = Q$ -value for ground state decay.

The integrals of the Eqs.(2.51) and (2.52) are solved analytically by parameterizing the above calculated potential $V(R)$, as follows:

$$V(R) = \begin{cases} a_1 R + a_2 R^2, & R_0 \leq R \leq R_t, \\ V(R_t) + m(R - R_t), & R_t \leq R \leq R_m, \\ V_B - \frac{1}{2}k(R - R_B)^2, & R_m \leq R \leq R_h, \\ V(R_h) - c_1 \frac{R - R_h}{R}, & R_h \leq R \leq R_i, \\ V(R_i) - c_2 \frac{R - R_i}{R}, & R_i \leq R \leq R_b, \end{cases} \quad (2.53)$$

For a polynomial of degree higher than two, analytical solutions of WKB integrals could not be obtained. The polynomial equation above is true for any inner turning point and hence R_t could be chosen empirically at any point on the poly-

mial part, as was shown by in [15]. Equation (2.53) means that, the first part of the potential from R_0 to R_t (or R_{emp}) is a polynomial of degree two in R , the second part from R_t to R_m is a straight line of slope ' m' ', the top part between R_m and R_h being an inverted harmonic oscillator and the rest from R_h to R_i and R_i to R_b are the Coulomb potentials of the type $1/R$. Finally, V_B and R_B give the height and position of the barrier. The analytical solution for the integrals are obtained as

$$\int_{R_b}^{R_t} V(R)dR = \int_{R_m}^{R_t} V(R)dR + \int_{R_h}^{R_m} V(R)dR + \int_{R_i}^{R_h} V(R)dR + \int_{R_b}^{R_i} V(R)dR \quad (2.54)$$

For different components of Eq.(2.50), we have

$$\begin{aligned} P_i = & \exp\left[-\frac{2}{\hbar}\sqrt{2\mu}\left\{\frac{\sqrt{a_2}}{2}[t_1(t_1^2 - L^2)^{\frac{1}{2}} - t_2(t_2^2 - L^2)^{\frac{1}{2}}\right.\right. \\ & \left.- L^2(\cosh^{-1}(\frac{t_1}{L}) - \cosh^{-1}(\frac{t_2}{L}))\right] \\ & + \frac{2}{3}\left(\frac{R_m - R_t}{V(R_m) - V(R_t)}\right)[(V(R_m) - V(R_i))^{\frac{3}{2}} - (V(R_t) - V(R_i))^{\frac{3}{2}}] \\ & - \frac{1}{\sqrt{2k}}[V_B - V(R_i)][\Theta_2 - \frac{1}{2}\sin 2\Theta_2 - \Theta_1 + \frac{1}{2}\sin 2\Theta_1] \\ & \left. + \sqrt{C_1 R_h R_i}[\Theta_3 - \frac{1}{2}\sin 2\Theta_3]\right\}] \end{aligned} \quad (2.55)$$

with

$$a_1 = \frac{R_0(Q - V(R_t))}{R_t(R_t - R_0)}, a_2 = -\frac{a_1}{R_0}, t_1 = R_t - \frac{1}{2}R_0, t_2 = R_{emp} - \frac{1}{2}R_0$$

$$L^2 = \frac{1}{4}R_0^2 + R_t(R_t - R_0) \left[\frac{Q - V(R_i)}{Q - V(R_t)} \right]$$

$$\Theta_1 = \cos^{-1} \frac{R_m - R_B}{\sqrt{\alpha_2}}, \Theta_2 = \cos^{-1} \frac{R_h - R_B}{\sqrt{\alpha_2}}, \Theta_3 = \tan^{-1} \left(\frac{R_i - R_h}{R_h} \right)^{1/2}$$

$$\alpha_2 = \frac{2}{k} [V_B - V(R_i)]$$

$$k = \frac{2\{[(V_B - V(R_m))]^{1/2} + [V_B - V(R_h)]^{1/2}\}^2}{(R_m - R_h)^2}, C_1 = R_i \frac{(V(R_h) - V(R_i))}{R_i - R_h}$$

and

$$P_b = \exp \left[-\frac{2}{h} \sqrt{2\mu} \sqrt{C_2 R_i R_b} \left\{ \Theta_4 - \frac{1}{2} \sin 2\Theta_4 \right\} \right] \quad (2.56)$$

with

$$\Theta_4 = \tan^{-1} \left[\frac{R_b - R_i}{R_i} \right]^{1/2},$$

$$C_2 = \frac{R_b [V(R_i) - V(R_b)]}{R_b - R_i}.$$

Substituting these values in Eqs. (2.51) and (2.52) we get P_i and P_b . Further substituting P_i and P_b in Eq. (2.50) we get the probability of penetration or the tunnelling probability, P .

2.5 The Preformed Cluster Model for ground state decay of nuclei

The existing theoretical models for exotic cluster decay of nuclei, generally fall under two categories: the unified fission model (UFM) and the preformed cluster model (PCM). Although the presumptions of UFM and the PCM are completely different but both seem to be working nicely in order to understand the spontaneous cluster-decay process. In the *UFM*, the cluster decay is dealt simply as a barrier penetration problem, whereas in the *PCM* it is considered to happen in two steps as mentioned in section 2.1. Preformed Cluster Model of Gupta and [10]- [18] has been developed by adopting the Gamow's theory of α -decay. Here, instead of a square well potential, a more realistic nuclear potential, the nuclear proximity potential, is used and also a preformation probability P_0 is associated with the size of the cluster. In Gamow's theory of α -decay, the preformation probability for α -decay is assumed to be unity, since only α -cluster is considered. In *PCM*, preformation probability is different for different clusters and it decreases with the increasing size of the cluster. It is relevant to mention here that theoretically the preformation probabilities for all the possible clusters can be obtained in *PCM*, whereas, in the other model due to Blendowske et al. [51, 54] the preformation probabilities are calculated for the cluster mass of up to only $A = 16$. The decay constant in the *PCM* of Gupta and collaborators is defined as,

$$\lambda = P_0 \nu_0 P. \quad (2.57)$$

The corresponding half life is given by:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}. \quad (2.58)$$

PCM here gives the ground state description ($\ell=0$ and $T=0$) of the decay of parent nuclei, with deformation and orientation effects of daughters and clusters included in it. P_0 is preformation probability of the cluster giving the probability of the formation of the cluster within the parent nucleus, which is also shown to carry the effects of deformations and orientations of outgoing fragments. For a pure Coulomb potential and $P_0 = 1$, the above equation (2.53) will give the Gamow factor ' λ_G '. Thus, in contrast to the unified fission models, the clusters in *PCM* are considered to be preformed with probability P_0 , at a relative separation measured in terms of co-ordinate R before the penetration of the potential barrier. Here ν_0 is the impinging frequency with which the cluster hits the barrier, defined as,

$$\nu_0 = \frac{v}{R_0} = \frac{(2E_2/\mu)^{1/2}}{R_0}, \quad (2.59)$$

where R_0 is the radius of parent nucleus and $E_2 = \frac{1}{2}\mu v^2$ is the kinetic energy of the emitted cluster. Since both the emitted cluster and the daughter nucleus are produced in the ground state, the entire positive Q -value is equal to total kinetic energy ($Q = E_1 + E_2$) available for the decay process. This kinetic energy is shared between two fragments and the energy of emitted cluster can be calculated as

$$E_2 = \frac{A_1}{A}Q \quad (2.60)$$

and, $E_1 = Q - E_2$ is the recoil energy of the daughter nucleus.

In equation 2.57, P is the penetration probability that gives the probability of penetration of the barrier formed by the outgoing deformed and oriented fragments.

2.6 The Dynamical Cluster-decay Model (DCM) for hot and rotating compound nucleus

The dynamical cluster decay model (*DCM*) [1]- [9] for the decay of a hot and rotating nucleus (i.e. angular momentum $\ell \neq 0$ and temperature $T \neq 0$) is a reformulation of the preformed cluster model (*PCM*) of Gupta and collaborators for ground-state ($\ell=0$, $T=0$) decay of a nucleus in cluster radioactivity (*CR*) and related phenomena [10]- [18]. Like *PCM*, *DCM* is also based on the dynamical (or quantum mechanical) fragmentation theory of cold phenomenon in heavy ion reactions and fission dynamics. In *DCM*, besides the temperature and angular momentum effects in the decay of excited compound nucleus, the deformation and orientation effects of the decay products are also taken care.

The *DCM*, the collective coordinates of mass asymmetry $\eta = \frac{A_1 - A_2}{A_1 + A_2}$ and relative separation R , respectively, give

- (i) the nucleon-division (or -exchange) between outgoing fragments, and
 - (ii) the transfer of kinetic energy of incident channel ($E_{c.m.}$) to internal excitation (total excitation or total kinetic energy, TXE or TKE) of the outgoing channel.
- It may be noted that the fixed decay point $R = R_a$ (defined later), at which the process is calculated, depends on temperature T as well as on η (i.e. $R(T, \eta)$). This

energy transfer process is defined by the following equation (see Fig. 3.1).

$$E_{CN}^* + Q_{out}(T) = TKE(T) + TXE(T). \quad (2.61)$$

The CN excitation energy $E_{CN}^* = E_{c.m.} + Q_{in}$ is related to temperature T (in MeV) as given by Eq.(2.22).

Using the decoupled approximation to R- and η -motions, the *DCM* defines the decay or fragment formation cross section, in terms of partial waves, as [2]- [8]

$$\sigma = \sum_{\ell=0}^{\ell_c} \sigma_{\ell} = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_c} (2\ell + 1) P_0 P; \quad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (2.62)$$

where, P_0 , the preformation probability, refers to η -motion and P , the penetrability, to R-motion. Here the complex (both light and heavy) fragments are treated as the dynamical collective mass motion of preformed clusters or fragments through the barrier. The structure information of the CN enters the model via the preformation probabilities P_0 (also known as the spectroscopic factors) of the fragments, given by the solution of stationary Schrödinger equation in η , at the fixed $R=R_a$, the first turning point of the penetration path shown in Fig. 3.1 for different ℓ -values.

$$\left\{ -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V(R, \eta, T) \right\} \psi^{\nu}(\eta) = E^{\nu} \psi^{\nu}(\eta), \quad (2.63)$$

with $\nu=0,1,2,3,\dots$ referring to ground-state ($\nu = 0$) and excited-states solutions.

For the decay of a hot CN , we use the postulate for the first turning point

$$R_a(T) = R_t + \Delta R(T) \quad (2.64)$$

where

$$R_t = R_1 + R_2 \quad (2.65)$$

$\Delta R(T)$ is the neck-length parameter that assimilates the neck formation effects. This method of introducing a neck length parameter is similar to that used in both the scission-point [55] and saddle-point [56,57] statistical fission models. The R_i are radius vectors given by Eqs.(2.14) and (2.15).

The potential $V(R_a)$ corresponding to $R_i R_a$ acts like an effective Q-value, Q_{eff} , for the decay of the hot CN at temperature T, to two exit-channel fragments observed in *g.s.* (T=0), defined by

$$\begin{aligned} Q_{eff}(T) &= B(T) - [B_L(T=0) + B_H(T=0)] \\ &= TKE(T) = V(R_a(T)) \end{aligned} \quad (2.66)$$

with B's as the respective binding energies.

The above defined decay of a hot *CN* into two cold (T=0) fragments, via Eq.(2.66), could apparently be achieved only by emitting some light particle (s) (*LPs*), like n, p, α , or γ -rays of energy

$$\begin{aligned} E_x &= B(T) - B(0) = Q_{eff}(T) - Q_{out}(T=0) \\ &= TKE(T) - TKE(T=0) \end{aligned} \quad (2.67)$$

which is zero for the *g.s.* decay, like for exotic CR. Note that the second equality in Eq. (2.67) is not defined for a negative $Q_{out}(T=0)$ system since the negative TKE(T=0) has no meaning. Apparently, Eq. (2.67) w.r.t (2.66) suggests that

the emission of light-particles starts early in the decay process. The exit channel fragments in Eq. (2.66) are then obtained in the ground-state with $TKE(T=0)$, as can be seen by calculating $E_{CN}^* - E_x$:

$$E_{CN}^* - E_x = |Q_{out}(T)| + TKE(T=0) + TXE(T). \quad (2.68)$$

The excitation energy $TXE(T)$ (not treated here) is used in, the secondary emission of light particles from the fragments which are otherwise in their ground states with $TKE(T=0)$ in the radial motion.

Thus, by defining $Q_{eff}(T)$ as in Eq. (2.66), in this model we treat the LP emission at par with the heavy fragments, called intermediate mass fragments (*IMFs*) emission. Thus, in this model a non-statistical dynamical treatment is attempted for not only the emission of *IMFs* but also of multiple *LPs*, understood so-far only as the statistically evaporated particles in a *CN* emission. It may be reminded here that the statistical model (*CN* emission) interpretation of *IMFs* is not as good as it is for the LP production [55]- [60].

In terms of $Q_{eff}(T)$, the second turning R_b satisfies (see Fig. 3.1)

$$V(R_a, \ell) = V(R_b, \ell) = Q_{eff}(T, \ell) = TKE(T). \quad (2.69)$$

with the ℓ -dependence of R_a defined by

$$V(R_a, \ell) = Q_{eff}(T, \ell = 0), \quad (2.70)$$

which means that the R_a , given by Eq. (2.70), is the same for all ℓ -values, and

that $V(R_a, \ell)$ acts like an effective Q-value, $Q_{eff}(T, \ell)$, given by the total kinetic energy $TK E(T)$. Then, using (2.69), $R_b(\ell)$ is given by the ℓ -dependent scattering potentials, at fixed T is given by Eq.(2.12), which is normalized to the exit channel binding energy $B_L(T) + B_H(T)$. Such a potential is illustrated in Fig. 3.1 (Chapter 3), for $^{202}\text{Pb} \rightarrow ^{101}\text{Nb} + ^{101}\text{Nb}$, at different ℓ -values.

The collective fragmentation potential $V(R, \eta, T)$ in Eq. (2.63) is given by Eq. (2.13). The mass parameters $B_{\eta\eta}(\eta)$, representing the kinetic energy part in Eq. (2.63), are the smooth classical hydrodynamical masses [47], given by Eq. (2.39).

Finally, the ℓ_c -value in Eq. (2.62) is the critical ℓ -value, in terms of the bombarding energy $E_{c.m.}$, the reduced mass μ and the first turning point R_a of the entrance channel η_{in} , given by

$$\ell_c = R_a \sqrt{2\mu[E_{c.m.} - V(R_a, \eta_{in}, \ell = 0)]}/\hbar, \quad (2.71)$$

or, alternatively, it could be fixed for the vanishing of fusion barrier of the incoming channel, called ℓ_{fus} , or else the ℓ -value (ℓ_{max}) where the light-particle cross section $\sigma_{LP} \rightarrow 0$. This, however, could also be taken as a variable parameter [56, 61].

It may be noted that the only parameter of the model is neck-length parameter ΔR , and ℓ_{max} value is accordingly decided in reference to this free parameter.

2.6.1 Barrier lowering (ΔV_B)

The choice of neck-length parameter (ΔR) [15] for the best fit to the data (on ER) allows us define the effective “barrier lowering” parameter $\Delta V_B(\ell)$ for each ℓ as the difference between the actually used barrier $V(R_a, \ell)$ and the top of the barrier

$V_B(\ell)$, as

$$\Delta V_B(\ell) = V(R_a, \ell) - V_B(\ell). \quad (2.72)$$

Since ΔV_B is defined as a negative quantity, the actually used barrier is effectively lowered, as is also illustrated in Fig.4.1 for both ℓ_{min} and ℓ_{max} values.

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Chapter 3

Decay of $^{202}\text{Pb}^*$ formed in

$^{48}\text{Ca} + ^{154}\text{Sm}$ reaction

3.1 Introduction

The complex process of fusion of two heavy nuclei can be best understood via the decay products of the compound nucleus (CN), such as the fusion-evaporation residue (ER) consisting of multiple light-particles n, p, α and γ -rays ($A \leq 4$), complex intermediate mass fragments (IMF) of masses $5 \leq A \leq 20$ with charges $2 < Z < 10$, the CN-fission or fusion-fission (FF) process, and the competing non- CN, fission-like decay processes of quasi-fission (QF) and deep-inelastic collisions (DIC). The FF decay channel comprises the symmetric fission (SF) fragments of mass region $A_{CN}^*/2 \pm 20$, the asymmetric or near-symmetric fission (nSF) and/or the heavy mass fragments (HMF). The competing non-CN, QF is considered not to lose its entrance channel identity, and its contribution is large w.r.t., say, FF in some reactions such as ^{48}Ca plus heavy actinides forming the superheavy elements with $Z = 112, 114$ and

116 (see, e.g., Ref. [1]; here QF cross-section σ_{QF} is termed as capture cross-section σ_{cap}). The interesting result of experiments is that different mass regions of compound nuclei show different combinations of the above mentioned decay processes or any one of them as a dominant decay mode. In the dynamical cluster-decay model (DCM) of Gupta and collaborators [2]- [13] all these decay products are treated on equal footing as the dynamical collective mass motions of preformed fragments or clusters through the barrier, except for the non-CN QF process where the incoming channel is kept (i.e., has the preformation probability $P_0 = 1$) and tunnels its own interaction barrier. In the alternative available statistical models, the light-particles (LP) emission is treated as an evaporation process in Hauser Feshbach (HF) analysis [14] and all other heavier mass fragments (IMF, HMF, nSF and SF) by either extending the HF analysis [15,16] or as a binary statistical fission process [17,18]. In the last more than three decades, many experimental and theoretical advancements have been made to understand the heavy ion reaction dynamics, and the related nuclear reaction properties.

The decay of CN $^{202}Pb^*$ formed in $^{48}Ca + ^{154}Sm$ reaction channel has been investigated recently [19, 20] and the fusion-fission cross-sections σ_{FF} and quasi-fission cross-sections σ_{QF} are measured at a number of near- and below-barrier energies. The fusion-evaporation residue cross-sections σ_{ER} were measured earlier in the same experiment [21]. Such reactions were motivated to study the role of the entrance channel mass-asymmetry, target nucleus deformation and neutron excess of the projectile, in comparison to, say, $^{48}Ca + ^{144}Sm$ reaction, and to compare its results with the similar ^{48}Ca based reactions on heavy deformed actinides forming superheavy nuclei, mentioned above [1]. In the reactions ^{48}Ca -plus-actinides, the

ER cross-sections are very small (in pb) compared to σ_{FF} and σ_{QF} (in mb), and that $\sigma_{QF} > \sigma_{FF}$ by at least one order of magnitude, almost independent of CN excitation energy E_{CN} . On the other hand, in the $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction the three decay processes (ER, FF and QF) are quite comparable (all in mb) at low excitation energies, ER being the most dominant, but at higher excitation energies the FF becomes most probable followed by ER and QF. However, at (nearly) the same excitation energy, but at above barrier energies, no QF component is measured in the $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction, perhaps because both the nuclei are spherical. Note that at the very high excitation energies, QF channel is also not observed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction. All these observed facts, make this reaction an interesting choice for its theoretical analysis on DCM. The DCM is very recently used successfully for the decay of $^{292}114^*$ formed in $^{48}\text{Ca} + ^{244}\text{Pu}$ reaction [11].

Another interesting aspect of the chosen $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction, and other similar reactions like $^{48}\text{Ca} + ^{144}\text{Sm}$ and $^{40}\text{Ca} + ^{154}\text{Sm}$, is the possible role of shell effects [20] (and also the effects of entrance channel) in mass distributions (MD) of the decaying CN (here ^{202}Pb , ^{192}Pb , and ^{194}Pb , respectively) in the neighborhood of QF process, observed as "shoulders" to the Gaussian FF distribution. The presence of such shell effects (magic shells) determines that the QF channel is actually fixed by the shell structure responsible for the nSF component in FF (=nSF+SF channels). In $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction [19] at the two lowest excitation energies ($E_{CN} = 49$ and 57 MeV), these "shoulders", referring to nSF component, are peaked around $A = 65$ and 140 , and hence fix the mass range ($A = 55$ - 145) of interest for both the FF and QF analysis. Apparently, the existence of both nSF and SF components in CN-fission, the FF process, calls for the fine structure in FF fragments, like the one

predicted earlier [9] in the decay of $^{246}\text{Bk}^*$.

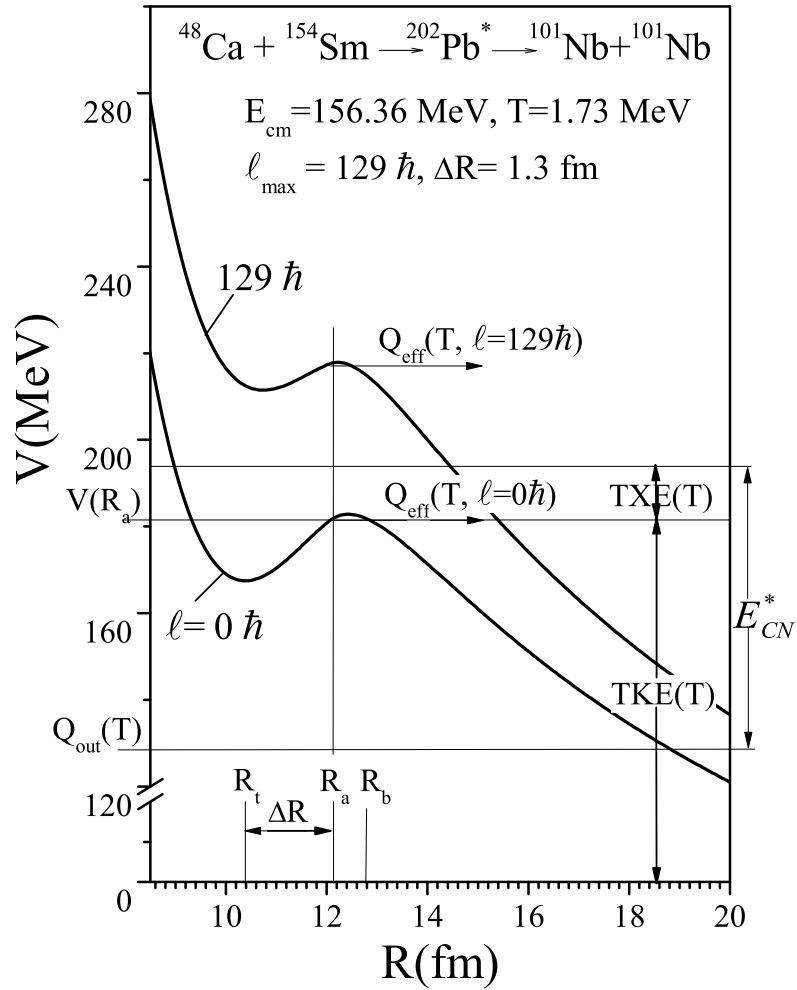


Figure 3.1 The scattering potential for the decay $^{48}\text{Ca} + ^{154}\text{Sm} \rightarrow ^{202}\text{Pb} \rightarrow ^{101}\text{Nb} + ^{101}\text{Nb}$ at temperature $T = 1.728 \text{ MeV}$ and different ℓ -values.

3.2 Calculations

The decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction is studied here at selected ten different $E_{\text{c.m.}}$ -values, taken from Refs. [19,21], over a wide range of $\approx 20 \text{ MeV}$ where experimental data for ER, FF and QF are available. It is important to note that the selected range of energies correspond to above as well as below the

Coulomb barrier energy. Fig 3.1 shows the scattering potential for the decay of $^{48}\text{Ca} + ^{154}\text{Sm} \rightarrow ^{202}\text{Pb}^* \rightarrow ^{101}\text{Nb} + ^{101}\text{Nb}$ at temperature $T = 1.728$ MeV and different ℓ -values i.e $\ell=0$ and ℓ_{max} . For the decay of hot compound nucleus, the total kinetic energy TKE and total excitation energy TXE of fragments are related to CN excitation energy E_{CN} as $E_{CN} + Q_{out}(T) = \text{TKE}(T) + \text{TXE}(T)$. Here, for the incident center-of-mass energy $E_{c.m.}$, $E_{CN} = E_{c.m.} + Q_{in} = (A_{CN}^*/9)T^2 - T$, with temperature T in MeV and Q_{in} and Q_{out} are the Q-values for the incoming and outgoing channels. We have calculated the penetrability P for the fusion-evaporation residue σ_{ER} , the fusion-fission σ_{FF} and the quasi-fission σ_{QF} processes by using such scattering potentials.

Figure 3.2 shows the fragmentation potential for the decay of $^{202}\text{Pb}^*$ at $E_{c.m.} = 156.36$ MeV ($T = 1.728$ MeV) and at two extreme ℓ -values ($\ell = 0$ and ℓ_{max}). In order to fit the available experimental data, we have taken different ΔR values for the fragment mass regions of three possible decay processes of ER, FF and QF at each excitation energy (equivalently, temperature T). This choice clearly means to indicate [10, 11] that the three decay processes ER, FF and QF do not occur simultaneously, i.e., they occur in different time scales and evolve subject to the nature of dynamics of the CN. We note in Fig. 3.2 that the LP (x-neutrons, xn, $x = 1, 2, 3$ and α -particle) and IMF ($5 < A < 16$) are favored at $\ell = 0$, but nSF and SF become favorable at the higher ℓ values. At $\ell = \ell_{max}$, we observe strong minima for symmetric fragments (SF) $A = 81-101$ ($= A_{CN}^*/2 \pm 20$) together with the neighboring minima corresponding to near symmetric fission (nSF) fragments $A = 65-75$. The sum of SF and nSF windows account for the total CN-fission or FF contribution. We shall see in the following that nSF window contributes significantly,

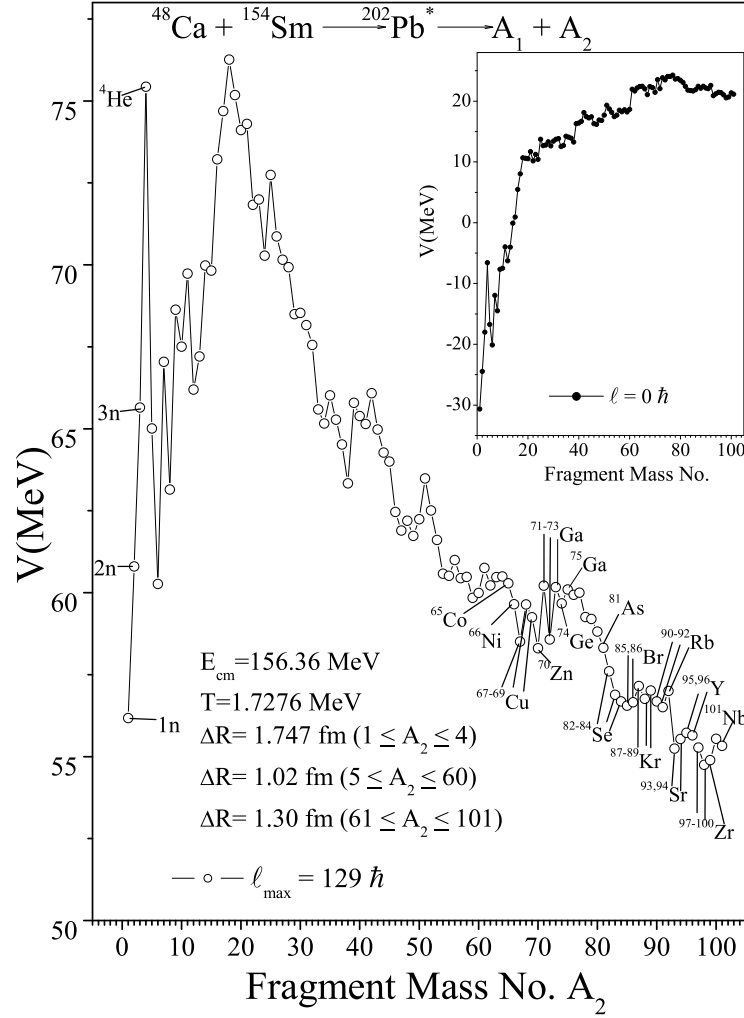


Figure 3.2 Fragmentation potential V as a function of the fragment mass number A_2 for the decay of ^{202}Pb , calculated at two extreme ℓ -values. The $\ell = 0$ case is shown as an inset.

with a maximum of up to $\sim 20\%$, for the lowest $E_{c.m.}$ values. In other words, there are strong indications of fine or sub-structure in the fission of CN $^{202}\text{Pb}^*$.

The preformation probability $P_0(A_2)$ in Fig.3.3 also shows the same result of a favored asymmetric to favored symmetric fragmentation as ℓ -value increases. Similarly, the penetration probability P as function of fragment mass A_2 , $P(A_2)$, in Fig. 3.4 approaches the maximum value of unity for symmetric and near-symmetric fragments at higher ℓ -values. Also, for light particles the penetrability P depends strongly on ℓ value. These results play significant role in calculating the decay

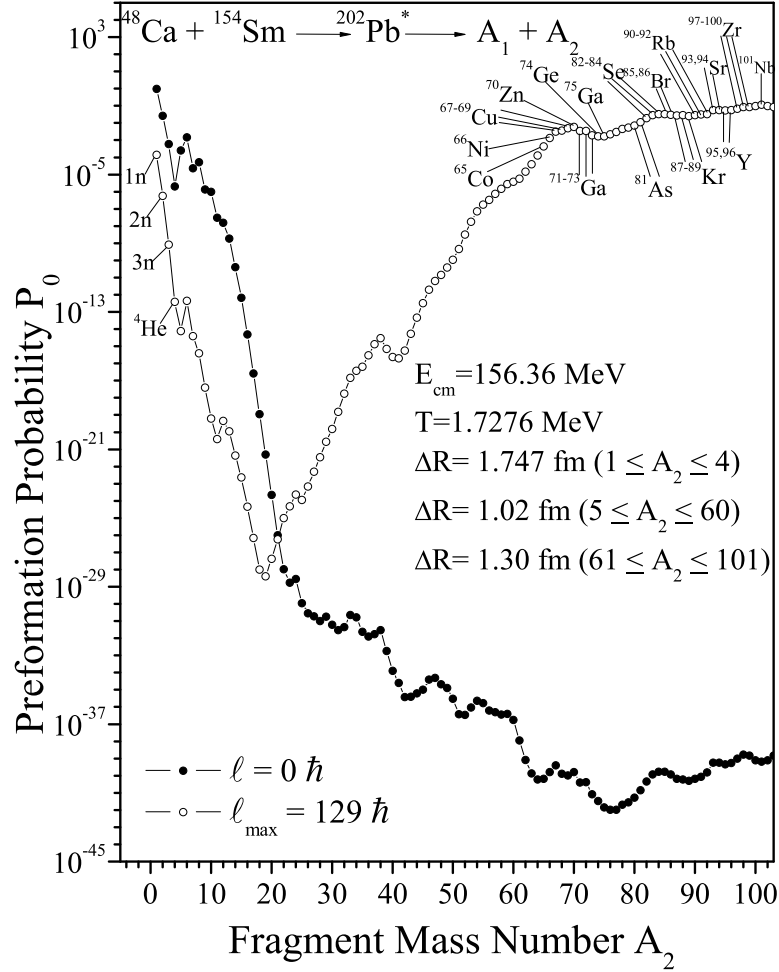


Figure 3.3 Preformation probability P_0 as a function of fragment mass number (A_2) for the decay of $^{202}\text{Pb}^*$, calculated by using the fragmentation potential of Fig. 3.2.

cross-sections.

Figure 3.5 shows the ℓ -summed upto $\ell = \ell_{\text{max}}$, preformation probability P_0 (hollow up triangles), penetration probability P (hollow circles) and the cross-section σ (solid circles) as functions of the fragment mass number A_2 , at $E_{\text{c.m.}} = 156.36 \text{ MeV}$ ($T = 1.73 \text{ MeV}$). We note that ℓ -summed P is almost constant as a function of fragment mass number and thus contributes mainly to the magnitude of cross-sections. On the other hand, P_0 shows an interesting structure with significant preformation factors for light particles as well as for near-symmetric and symmetric mass frag-

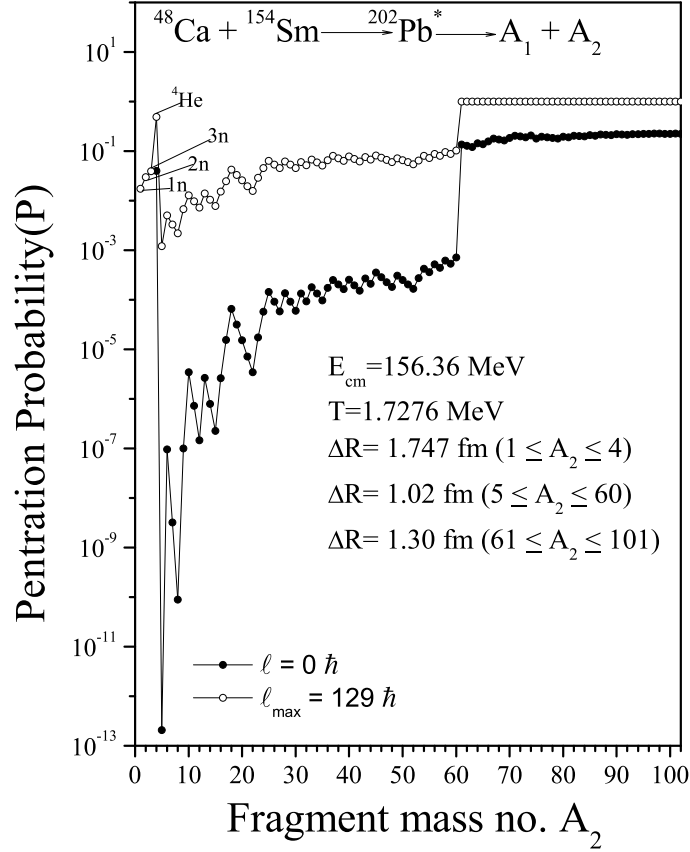


Figure 3.4 Same as for Fig. 3.3, but for the penetration probability P . For $\ell = 0$ case, P is nearly zero for the first three mass numbers $A_2 = 1$ to 3 (not plotted).

ments (nSF and SF), which is an important result for comparing our calculated decay cross-sections due to SF and nSF with the available FF data of Ref. [19]. It may be pointed out here that the fission fragments are not identified in the data, [19] and the reported CN-fission or FF cross-sections correspond to SF ($=A_{CN}^*/2 \pm 20$).

It is relevant to remind here that at the lower incident c.m. energies ($E_{c.m.} = 139.148$ MeV, equivalently, excitation energies $E_{CN} = 49.57$ MeV), the measured mass distributions (MD) for the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction show "shoulders" around the nSF mass region which are due to the non-CN decay, taken as QF contribution σ_{QF} to the total decay cross-sections. In our model calculations, however, we find that the nSF region contributes to FF cross-section as

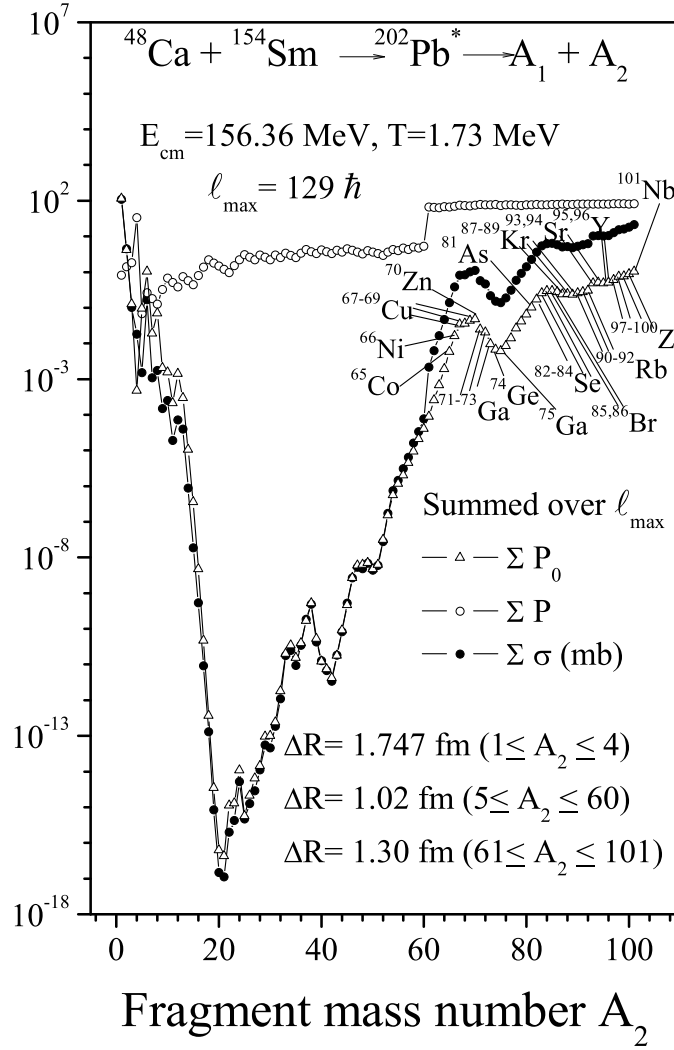


Figure 3.5 The ℓ -summed preformation probability P_0 , penetration probability P and cross-sections for the decay of $^{202}\text{Pb}^*$ as a function of fragment mass A_2 at $E_{c.m.} = 156.36$ MeV ($T = 1.728$ MeV).

well as to QF cross-section. In the following, we will see that, like for the nSF in Figs. 3.2 and 3.3, the "shoulders" in MD are also the manifestations of shell effects (magic numbers) in the formation yields. This result is further supported with the MD calculation showing no such "shoulders" for another reaction channel $^{48}\text{Ca} + ^{144}\text{Sm}$ forming CN $^{192}\text{Pb}^*$ at about the same incident c.m. energy $E_{c.m.}$ (hence, different E_{CN}).

In Fig. 3.6, the calculated cross-sections σ_{ER} , σ_{FF} (taken as $\sigma_{SF} + \sigma_{nSF}$) and σ_{QF} ,

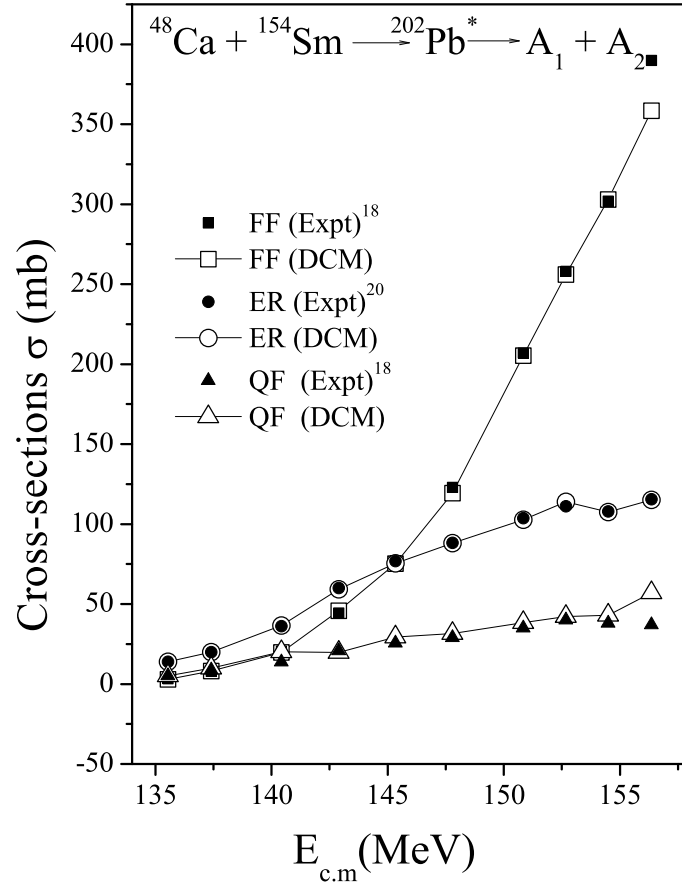


Figure 3.6 Comparison between the measured and calculated fusion-evaporation residue (ER), CN fission or fusion-fission (FF), and quasi-fission (QF) cross-sections. The data are from Refs. [19] and [21].

at different c.m. energies, are shown together with the experimental data [19,21] for comparisons. The same result is also presented in Table 3.1, as well as are given the other calculated quantities and fitted parameters. With in one parameter fitting, the calculations show an excellent comparison with data, except for one or two higher energy data in cases of QF and FF processes. Such a disagreement at the highest energy may perhaps be attributed to the non-inclusion of pre-fission neutron emission. The interesting feature of $^{202}\text{Pb}^*$ decay is that the ER, FF and QF cross-sections are quite comparable over a large range of lower energies, and that ER process is most dominant, giving way to FF process at higher energies.

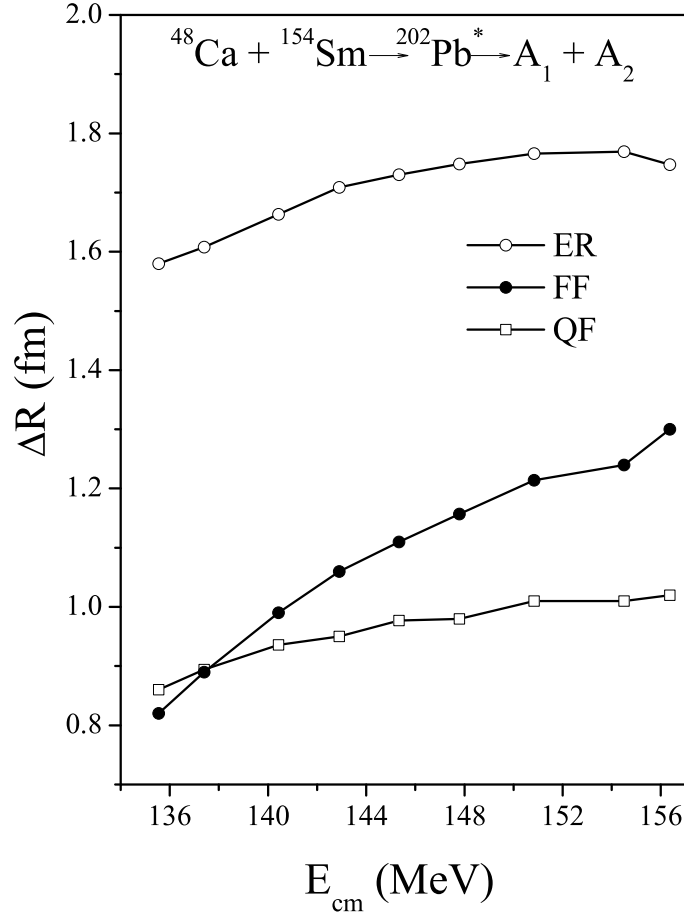


Figure 3.7 The fitted parameter ΔR for the evaporation residues (ER), fusion-fission (FF), and quasi-fission (QF) decay processes of ^{202}Pb as function of $E_{\text{c.m.}}$.

Figure 3.7 shows the fitted parameter ΔR for the three decay processes (ER, FF and QF) of $^{202}\text{Pb}^*$ as a function of $E_{\text{c.m.}}$. For all the three processes, we notice a linear increase in ΔR with increase of $E_{\text{c.m.}}$. Clearly the ER process occurs first, having largest values of ΔR . The FF and QF occur almost simultaneously at the lower energies, whereas at relatively higher energies the FF (having larger ΔR) seems to occur prior to QF. Therefore, one can conclude that, at least at lower c.m. energies, QF competes with FF process, though at higher energies the FF takes over QF process, as is observed in experiments.

Table 3.1 also presents the fine structure of two components (nSF and SF) of FF

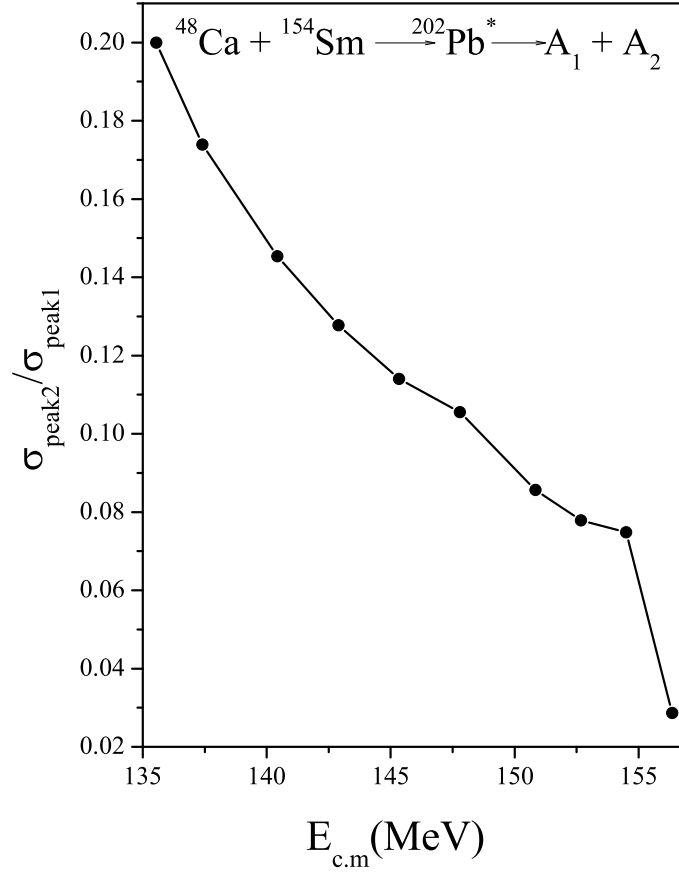


Figure 3.8 The ratio of peak values for SF (peak1) and nSF (peak2) windows as a function of $E_{c.m.}$.

process, as already noted above in connection with Fig. 3.2. This is explicitly shown in Fig. 3.8 where the peak to peak ratios for nSF and SF contributions are plotted as a function of $E_{c.m.}$. Peak1 refers to SF and peak2 to nSF. One clearly sees that nSF contribution is quite significant (of the order of $\sim 20\%$), at least for the first few lower c.m. energies. It is interesting to remind here that a similar fine structure effect observed in calculations [9] of CN $^{246}\text{Bk}^*$ was at higher c.m. energies only whereas here in the decay of $^{202}\text{Pb}^*$ the nSF contribution is more at lower incident c.m. energies. This is an important result which need an experimental verification, useful for understanding the dynamical behavior of different nuclear systems.

Finally, in order to analyze the role of magic shells in mass distributions (MD),

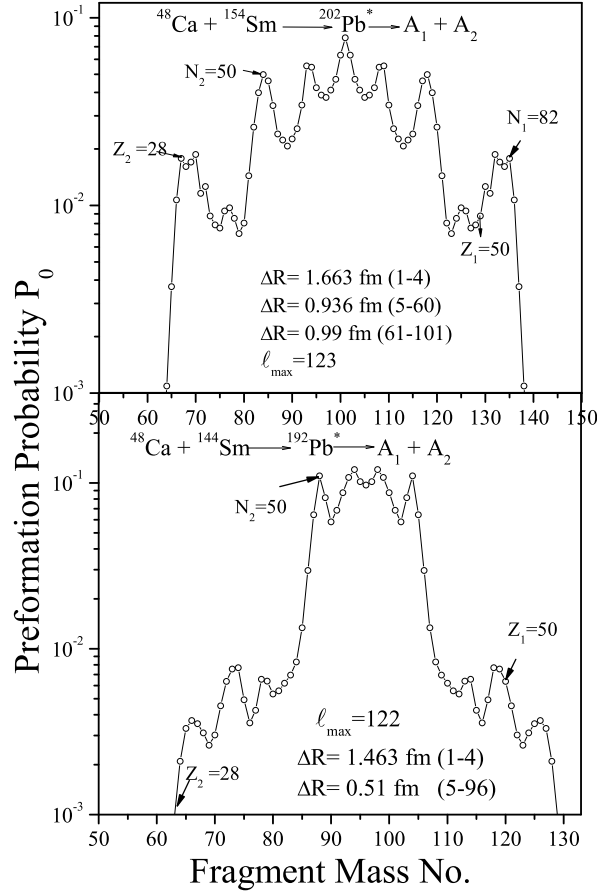


Figure 3.9 Mass distribution yields (equivalently, preformation probability P_0) for the decay of ^{202}Pb and ^{192}Pb formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ (upper panel) and $^{48}\text{Ca} + ^{144}\text{Sm}$ (bottom panel) reaction, respectively, at nearly the same c.m. energies (hence, different CN excitation energies). The measured mass distributions can be seen in Fig. 3 of Ref. [20] or Fig. 11 (top and bottom panels) of Ref. [19]. The magic shells contributing to "shoulders" are also marked.

we have calculated the fragment formation yields P_0 for the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ at an excitation energy $E_{\text{CN}} = 49$ MeV, compared with the same for $^{192}\text{Pb}^*$ due to $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction at $E_{\text{CN}} = 38$ MeV. The results are presented in Fig. 3.9, to be compared with measured MD's in Fig. 3 of Ref. [20] or Fig. 11 (top and bottom panels) of Ref. [19]. These CN excitation energies correspond to nearly the same c.m. energies (respectively, 140.43 and 143.61 MeV for $^{202}\text{Pb}^*$ and $^{192}\text{Pb}^*$ systems). It may be reminded here that in experiments [19] at these

excitation energies, clear signatures of near-symmetric fission (nSF) as "shoulders" are seen at $A = 65$ and 140 in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction (referring [20] to magic shells $Z_2 = 28$, $N_2 = 50$ in light fragment mass A_2 region, and $Z_1 = 50$, $N_1 = 82$ in heavy fragment mass A_1 region), but no such "shoulders" are identified in $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction [19] since the magic shells ($Z_2 = 28$) of only the light fragment come in to play [20]. Interestingly, Fig. 3.9 shows that the nSF yield (the "shoulders") is significant for $^{202}\text{Pb}^*$ in comparison to that for the neutron deficient $^{192}\text{Pb}^*$, in line with the experimentally measured MD's. The contributing magic shells for $^{202}\text{Pb}^*$, are $Z_2 = 28$ and $N_1 = 82$, referring to both the light and heavy fragments, but the same for $^{192}\text{Pb}^*$ do not show such features of "shoulders" contributing to nSF component. In other words, the calculated MD's in Fig. 3.9 clearly show the presence of "shoulders" due to QF process in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction, and an absence of the same in $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction. It may be mentioned here that the choice of neck-length parameter for $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction is almost arbitrary, i.e., obtained by extrapolating the results in Fig. 3.7 rather than by fitting to any data. Hence, the results presented in lower panel of Fig. 3.9 have the possibility to be improved further.

3.3 Summary

In this chapter, we have studied the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction at different center-of-mass energies, using the dynamical cluster-decay model (DCM) for spherical fragments. We find that the light-particles (fusion-evaporation residue) are favored at lower as well as higher angular momenta whereas the symmetric frag-

ments (SF) $A = 81-101$ ($=A_{CN}^*/2 \pm 20$) together with near-symmetric fragments (nSF) $A = 65-75$ are favored more at higher angular momenta. This window like structure indicates a fine- or sub-structure in the fusion-fission of compound nucleus $^{202}\text{Pb}^*$. The ℓ -summed penetrability P contributes mainly to the magnitude, playing no role in the structure of the cross-sections, whereas the ℓ -summed preformation probability P_0 shows an interesting structure with significant preformation factor for light particles as well as for SF and nSF in order for the cross-sections to compare nicely with the experimental data for ER cross-section σ_{ER} and the fusion-fission (or CN-fission) cross-section σ_{FF} ($= \sigma_{SF} + \sigma_{nSF}$). The contribution of nSF window is quite significant, of the order of $\sim 20\%$, for at least a few lower c.m. energies, and then decreases as energy increases, perhaps due to reduced shell effects at higher incident energies. The nSF window is shown to appear as "shoulders" in the otherwise Gaussian FF mass distribution, contributing to the non-compound-nucleus quasi-fission (QF) process. The nSF window (responsible for QF process) is shown to be due to the presence of shell effects (magic shells) in the mass distributions, further supported by its absence (also, no QF decay channel) in the mass-fragmentation preformation yield calculations for the decay of compound nucleus $^{192}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction.

The calculated ER, FF and QF cross-sections show excellent comparisons with the available experimental data, with in one parameter fitting of neck-length. The fitted neck-length parameters ΔR for all the three processes are shown to increase almost linearly with increase of $E_{c.m.}$. It represents an interesting nuclear dynamics of evaporation residue process occurring first (with larger values of ΔR), and fusion-fission competing with quasi-fission at lower energies but then the fusion-fission takes

over the quasi-fission process. Thus, in general, the three process occur in different time scales, though FF and QF occur almost simultaneously at lower energies.

Table 3.1 The decay cross-sections, σ_{ER} , σ_{FF} ($A_{CN}/2 \pm 20$, 65-75 and their complementary fragments) σ_{SF} ($\sigma_{SF} + \sigma_{nSF}$) and σ_{QF} calculated using DCM for different $E_{c.m.}$ in the reaction $^{48}\text{Ca} + ^{154}\text{Sm} \rightarrow ^{202}\text{Pb}^* \rightarrow A_1 + A_2$, compared with experimental data [19, 21] The characteristic quantities and fitted parameters are also given here for all the three decay processes.

$E_{c.m.}$	E_{CN}	T	l_{max}	ΔR_{ER}	$\sigma_{ER}(\text{mb})$		ΔR_{QF}	σ_{QF}		$\Delta R_{Fiss.}$	$\sigma_{Fiss.}(\text{DCM})$		$\sigma_{Fiss.}\text{expt.}$
(MeV)	(MeV)	(MeV)	($\hbar$)	(fm)	(DCM)	(EXP)	(fm)	DCM	(EXP)	(fm)	σ_{nSF}	σ_{SF}	(mb)
156.36	65.26	1.728	129	1.75	115.1	115.6 ± 2.5	1.02	57	37 ± 29	1.3	10	348.5	390 ± 21
154.5	63.4	1.703	126	1.77	107.5	107.9 ± 2.4	1.01	43	38 ± 23	1.234	21.1	281.9	302 ± 16
152.67	61.57	1.679	125	1.78	114	111.2 ± 2.2	1.01	42.1	40 ± 20	1.228	18.5	237.6	258 ± 14
150.84	59.74	1.654	125	1.77	102.8	103.7 ± 2.1	1.01	38.4	35 ± 16	1.215	16.2	189.2	207 ± 12
147.79	56.69	1.612	125	1.75	88.1	88.2 ± 1.6	0.98	31.5	29 ± 10	1.158	11.4	108	123 ± 7
145.34	54.24	1.577	124	1.73	75.4	76.9 ± 1.6	0.98	29.4	25.5 ± 6.7	1.115	7.7	67.5	77 ± 4.5
142.9	51.80	1.542	123	1.71	59.3	60.1 ± 1.0	0.95	19.7	20.7 ± 4.1	1.07	5.2	40.7	44.4 ± 2.6
140.43	49.33	1.505	123	1.66	36.5	36.2 ± 0.7	0.94	20.1	3.7 ± 2.1	0.99	2.5	17.2	20.5 ± 1.3
137.4	46.30	1.459	123	1.61	19.9	19.9 ± 0.6	0.89	9.9	8.8 ± 1.1	0.9	1.2	6.9	7.9 ± 0.7
135.55	44.45	1.430	122	1.58	13.9	14 ± 0.4	0.86	5.13	5.1 ± 0.5	0.82	0.5	2.5	3.3 ± 0.3

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Chapter 4

Barrier-lowering at sub-barrier energies and isospin effect of adding neutrons to decaying Pt^* nuclei formed in $^{64}Ni + ^{112-132}Sn$ reactions

4.1 Introduction

The formation and decay of a compound nucleus (CN) has been a topic of great interest for several decades as it provides useful information regarding fusion cross-section and its variation with incident center-of-mass energy $E_{c.m.}$, the fusion excitation functions. The fusion cross-section is a sum of the measured cross-sections

due to evaporation residue (ER), fission and related phenomena such as the quasi-fission (qf) and deep-inelastic collision (DIC) processes. In the standard statistical formalisms, the ER and fission are treated on two different models, the statistical evaporation codes and fission models, whereas the non-compound, qf process with incoming nuclei not losing their identity, could not be treated within the statistical models. On the other hand, the fusion excitation functions are, in general, nicely explained on the coupled channel calculation (ccc), using CCFULL code with inelastic excitation of both the projectile and target nuclei and neutron transfer included. The exceptions are the ER cross-sections in reactions such as $^{58,64}\text{Ni}+^{58,64}\text{Ni}$ and $^{64}\text{Ni}+^{100}\text{Mo}$ where, in true ccc, a new phenomenon of fusion hindrance is evidenced at sub-barrier energies [1]- [3]. Alternatively, the dynamical cluster-decay model (DCM) of one of us (RKG) and collaborators [4]- [12] described in Chapter 2 treat all the decay processes (ER, fission and qf) on equal footings as barrier penetration of preformed fragments or clusters. The DCM also supports the only acceptable explanation for the above said hindrance phenomenon in ccc in terms of the modified shape of potential inside the barrier at sub-barrier energies [2, 3], since the property of lowering of barriers (without modifying the depth of potential pocket) at sub-barrier energies arises in DCM in a simple way [10, 12] via its fitting of the neck-length parameter, as will be discussed below.

In this chapter, we have used the DCM to study the decay of $^{176,182,188,196}\text{Pt}^*$ nuclei formed in the ^{64}Ni -based reactions $^{64}\text{Ni}+^{112,118,124}\text{Sn}$ and $^{132}\text{Sn}+^{64}\text{Ni}$, where both the ER and fission cross-sections are measured at the near and below-barrier energies [13, 14]. These reactions are of interest for the following four reasons, at least: (i) First of all, the use of neutron-rich, radioactive ^{132}Sn beam opens up the

possibility of studying the phenomenon like the sub-barrier fusion enhancement, with the increase of N/Z ratio of the CN (^{124}Sn is the heaviest stable Sn-nucleus, with eight neutrons less than that of ^{132}Sn). At sub-barrier energies, for all the four reactions, the ER cross-sections are measured to be larger than the corresponding fission cross-sections. For $^{132}Sn + ^{64}Ni$ reaction, however, only the ER cross-section is measured as the fission of $^{196}Pt^*$ is not observed at sub-barrier energies. Our analysis of the ER cross-sections on the basis of the DCM shows that the neutron-rich, radioactive nature of ^{132}Sn nucleus becomes evident from the smaller neck-length parameter, which means a different reaction-time scale, predicted for this reaction. Similarly, for fission mass distributions, the DCM predicts a change from predominantly symmetric fission (SF) for $^{176,182}Pt^*$ to predominantly asymmetric fission (AF) for $^{188,196}Pt^*$ systems, i.e., the SF-distribution goes over to AF-distribution with the increase in iso-spin ratio N/Z of the CN. (ii) Secondly, the presence of qf component in fission cross-section need be investigated. In spite of the possible contribution from the deep inelastic collisions being evident in these experiments, the qf component could not be separated from fission, in particular for $^{132}Sn + ^{64}Ni$ reaction because of the inverse kinematics and the beam intensity being several orders of magnitude lower than that of the stable Sn-beams. However, within the DCM calculations, made for quadrupole (β_2) deformed fragments having optimal orientations (θ_{opt}) for hot (compact) configurations [15], there is a significant contribution of qf at the highest two energies for the heaviest two compound systems $^{188,196}Pt^*$, whereas the same is found at only the highest energy in the remaining two lighter systems $^{176,182}Pt^*$. (iii) Since these reactions are also ^{64}Ni -based, it will be of interest to see, with in the DCM, if barrier-lowering effects are essential

for fitting the ER cross-sections in these reactions also, like in $^{58,64}\text{Ni}+^{58,64}\text{Ni}$ and $^{64}\text{Ni}+^{100}\text{Mo}$ [10, 12]. The important point to note is that a ccc, including neutron transfer and inelastic excitation of the projectile and target (CCFULL), and the density-constrained TDHF (DCTDHF) calculation, reproduce the measured excitation functions only to a reasonable extent since there are deviations (under- and over-estimation) at the above, near and below-barrier energies [13, 14]. (iv) Finally, through our use of the DCM, where the fragments are quadrupole deformed having optimum orientations [15], we are interested in seeing the effects of collective clusterization of preformed clusters in these reactions.

The calculations and results are discussed in section 4.2. Finally the results are summarized in section 4.3.

4.2 Calculations and Results

The decay of $^{176,182,188,196}\text{Pt}^*$ nuclei is measured [13, 14] over a wide range of c.m. energies (142.5-205 MeV), both below as well as above the Coulomb barrier. Fig.4.1 shows the scattering potential for the decay $^{132}\text{Sn}+^{64}\text{Ni}\rightarrow^{196}\text{Pt}^*\rightarrow^{195}\text{Pt}+\text{x}(\text{x}=1\text{n or }^1\text{H})$ at $E_{c.m.}=165.5$ MeV and at two different ℓ -values, the ℓ_{min} and ℓ_{max} . In Fig.4.1 R_a is defined as the first turning point(s) of the penetration path(s), used for calculating the WKB penetrability P for two ℓ_{min} and ℓ_{max} values. The choice of neck-length parameter (ΔR) [16, 17] for the best fit to the data (on ER) allows us define the effective "barrier lowering" parameter $\Delta V_B(\ell)$ for each ℓ as the difference between the actually used barrier $V(R_a, \ell)$ and the top of the barrier $V_B(\ell)$, as discussed in Eq. 2.72. Since ΔV_B is defined as a negative quantity, the actually

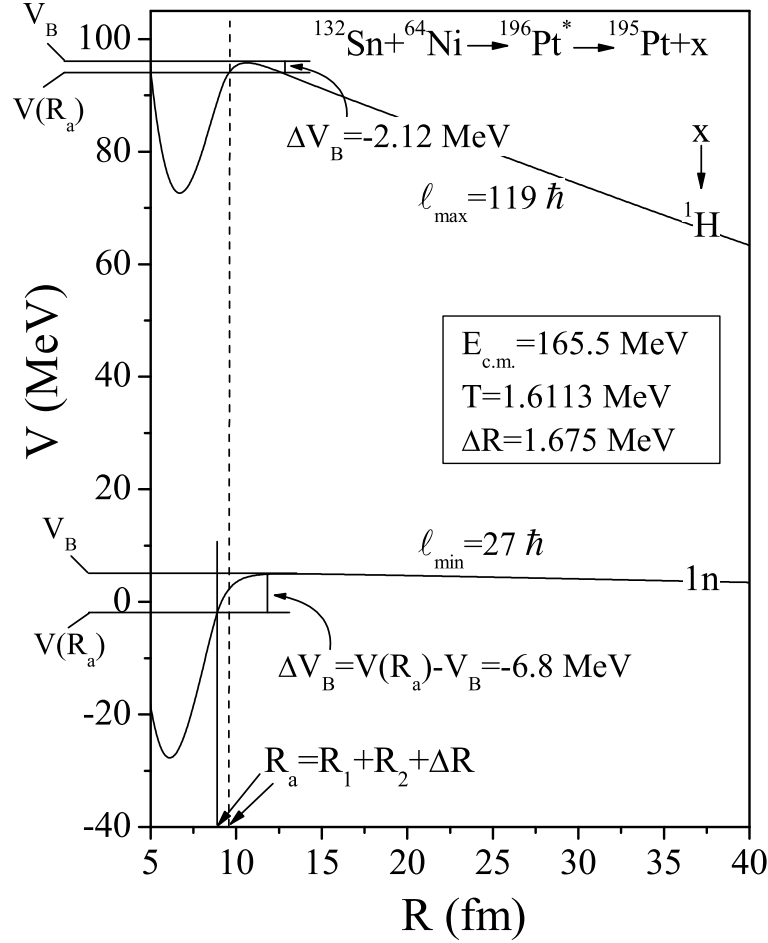


Figure 4.1 Scattering potential for the decay $^{132}Sn + ^{64}Ni \rightarrow ^{196}Pt \rightarrow ^{195}Pt + x$ ($x = 1n$ or ^1H) at $E_{c.m.} = 165.5$ MeV and at two different ℓ -values, the ℓ_{min} and ℓ_{max} . Note that the energetically favoured emitted particle is $1n$ for $\ell = \ell_{min}$ and ^1H for $\ell = \ell_{max}$.

used barrier is effectively lowered, as is also illustrated in Fig.4.1 for both ℓ_{min} and ℓ_{max} values. The ℓ_{min} and ℓ_{max} values are fixed for the ER (the light-particles) cross section $\rightarrow 0$. $\ell_{min} = 0$ for $A_2 \geq 4$, but for the lighter particles ($A_2 < 4$) it takes the value that starts to contribute to the penetrability P . For a comparative study of the decay mechanism of various Pt-isotopes, calculations are made at comparable c.m. energies $E_{c.m.} = 162.9-165.5$ MeV.

First of all, we look at the fragmentation potentials $V(A_2)$ in Fig. 4.2 for all the four systems, plotted for $\ell = 0$ and ℓ_{max} values. Calculations are made for different

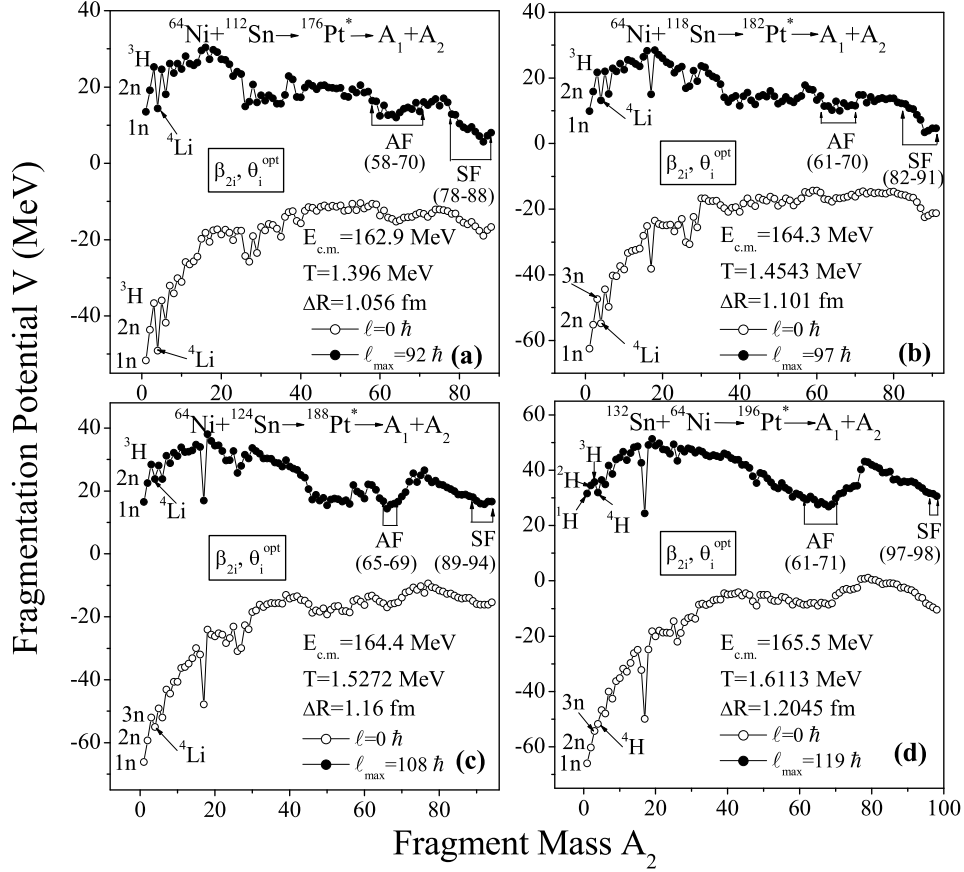


Figure 4.2 Fragmentation potentials $V(A_2)$ for the decay of $^{176,182,188,196}\text{Pt}^*$ nuclei, plotted for the extreme ℓ -values, with effects of quadrupole (β_{2i}) deformations and optimum hot (compact) orientations θ_i^{opt} included. The contributing fragments to symmetric and asymmetric fission (SF and AF) are also indicated in the body of the figure. For example, in the case of $^{176}\text{Pt}^*$ the SF corresponds to $A_2=78-88$ and AF to $A_2=58-70$, plus the complementary fragments $A_1 = A_{CN} - A_2$.

neck-length parameters ΔR , chosen to fit the respective experimental data (see Figs. 4.5 and 4.9). We notice three interesting results in Fig. 4.2: (i) For the first two lighter systems $^{176}\text{Pt}^*$ and $^{182}\text{Pt}^*$, the potential energy minima are stronger at the symmetric fragmentations, whereas the same are deeper at asymmetric fragmentations for the other two heavier systems $^{188}\text{Pt}^*$ and $^{196}\text{Pt}^*$. However, there is no noticeable change in the structure of $V(A_2)$ in going from $^{188}\text{Pt}^*$ to $^{196}\text{Pt}^*$ system, except in the characteristics of the emitted light particles, i.e., due to the additional

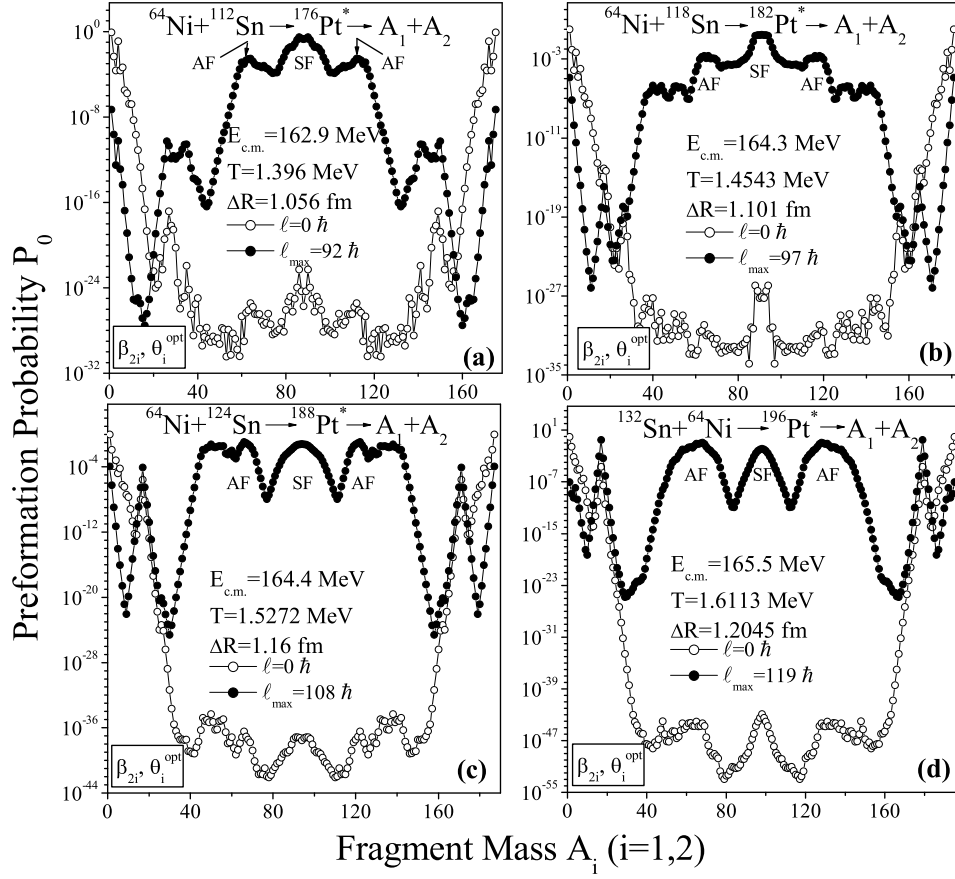


Figure 4.3 Preformation probability P_0 as a function of fragment mass A_i ($i=1,2$), for the fragmentation potentials of Fig. 4.2 for all the four systems $^{176,182,188,196}Pt^*$, i.e., with deformations β_{2i} and orientations θ_i^{opt} included.

eight neutrons of the neutron-rich radioactive beam ^{132}Sn , compared to stable ^{124}Sn beam, the ER changes, which seems to affect the best fitted neck-length parameters ΔR in two cases (see, later the discussion on Fig. 4.9). Note that the deeper minimum at ^{17}B fragment, in each case, does not contribute due to its negligible penetrability P value. (ii) We notice that only the ER contribution is most prominent at $\ell=0$, whereas at ℓ_{max} the fission fragments in the symmetric fission (SF) or asymmetric fission (AF) channels are more prominent. (iii) The contributing light particle(s) change in going from $\ell=0$ to ℓ_{max} (this is also illustrated in Fig. 4.1 for ℓ_{min} and ℓ_{max} values).

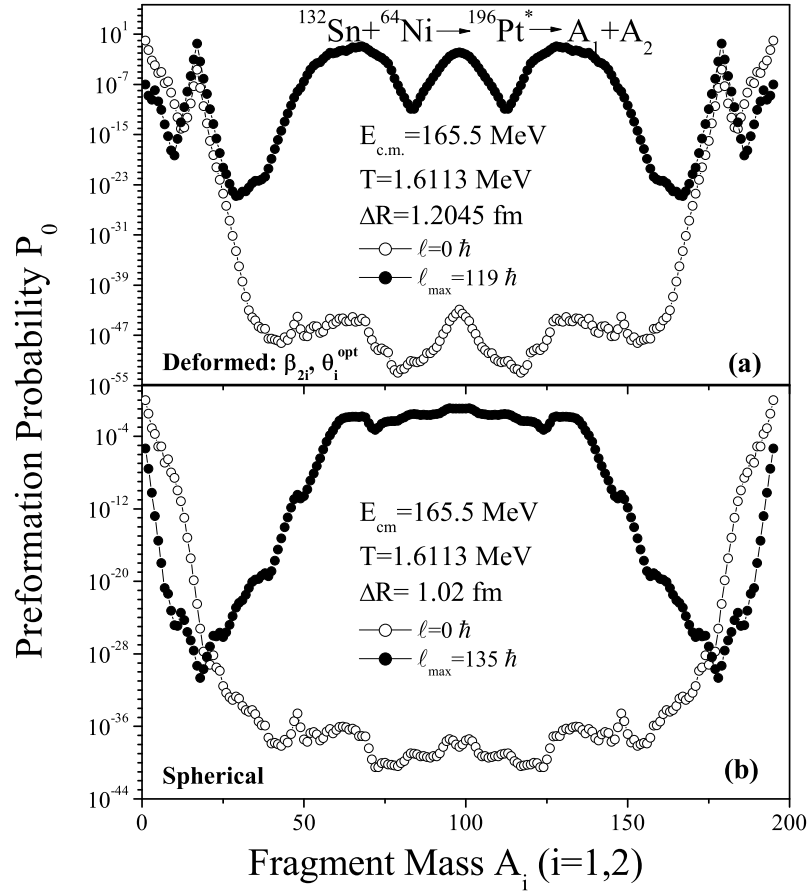


Figure 4.4 (a) Same as for Fig. 4.3, but for only $^{196}\text{Pt}^*$, compared in (b) with a similar calculation for spherical nuclei.

The above results are better presented in terms of the preformation factor $P_0(A_i)$ (i=1,2), plotted in Fig. 4.3 for the fragmentation potentials $V(A_2)$ of Fig. 4.2, and more explicitly in Tables 4.1-4.4 where the calculated contributions of different processes (ER and fission, both symmetric and asymmetric components) and other parameters of the DCM are presented, together with the available experimental data [13, 14]. From Tables 4.1 and 4.2 and Figs. 4.3(a) and (b), we notice that, in the decays of $^{176}\text{Pt}^*$ and $^{182}\text{Pt}^*$, the contribution of symmetric fission (SF) is much larger than that of the asymmetric fission (AF). The peak at AF is less than 1 % of the peak at SF. In other words, the decay of lighter $^{176,182}\text{Pt}^*$ isotopes is

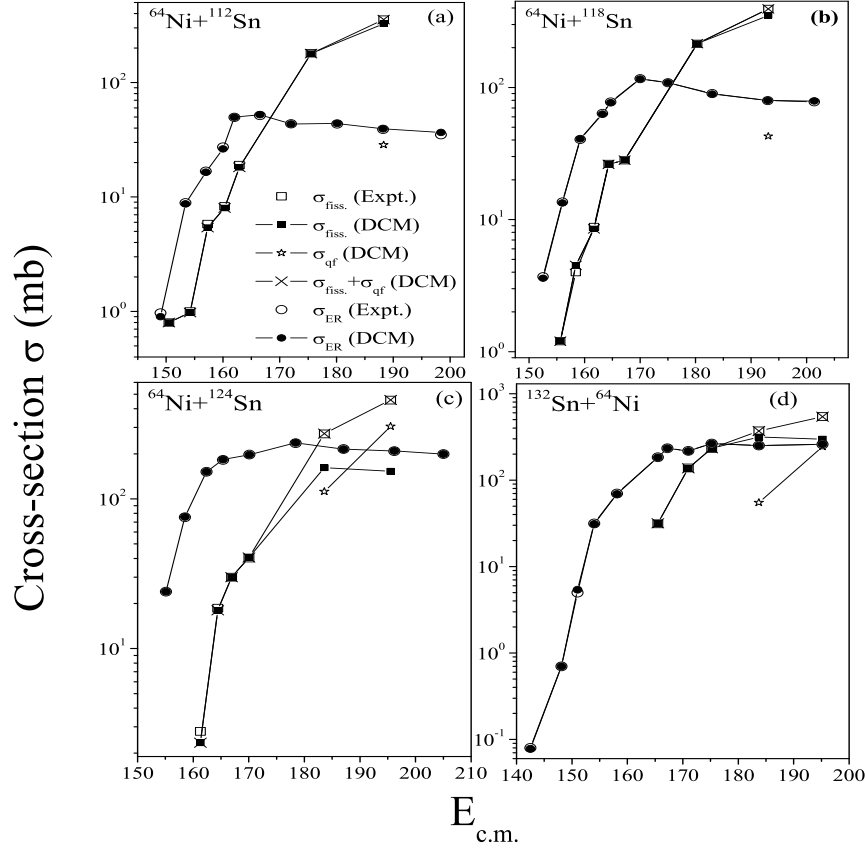


Figure 4.5 Comparison between the DCM calculated evaporation residue (ER) and fission cross-sections with experimental data [13, 14] for all the four Pt^* systems. The estimated quasi-fission (qf) component at the highest one or two energies is also shown, and the sum $\sigma_{fiss.} + \sigma_{qf}$ (DCM) compared with measured $\sigma_{fiss.}$ (Expt.) data.

predominantly via symmetric fission (SF). On the other hand, for the decays of $^{188}Pt^*$ and $^{196}Pt^*$ in Figs. 4.3(c) and (d) and Tables 4.3 and 4.4, the AF peak is quite prominent as compared to the SF peak. Specifically, in case of $^{188}Pt^*$, SF peak is less than 65% of AF peak (see, Table 4.3), and the same (SF), in the case of $^{196}Pt^*$, is almost negligible (less than 15%). These results clearly allow us to conclude that, the decays of $^{176,182}Pt^*$ lead to SF and those of $^{188,196}Pt^*$ to AF, i.e., the fission pattern changes from a symmetric to an asymmetric distribution with the increase in iso-spin ratio N/Z of the decaying CN. The fact that the predominantly

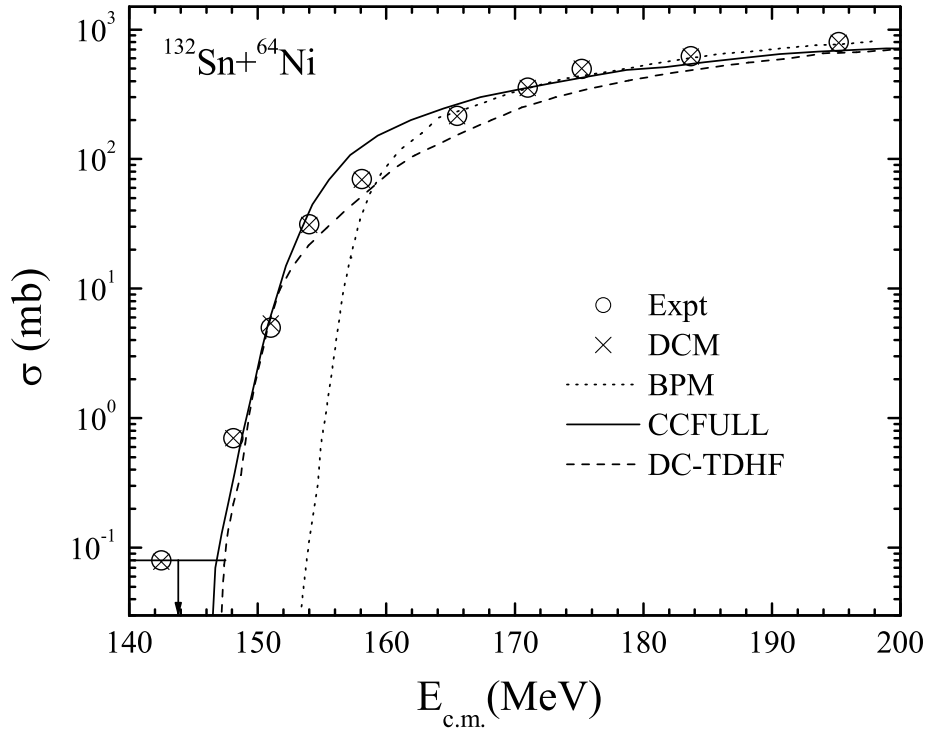


Figure 4.6 Comparison of DCM calculated fusion excitation function $\sigma_{fusion}(E_{c.m.})$, where $\sigma_{fusion} = \sigma_{ER} + \sigma_{fiss.} + \sigma_{qf}$, with other calculations (BPM, CCFULL and DC-TDHF) from [14], and the experimental data [14] for the decay of $^{196}Pt^*$ formed in $^{132}Sn + ^{64}Ni$ reaction.

SF or AF pattern arises due to the inclusion of deformation and orientation effects is evident from Fig. 4.4 where the results of a deformation-included calculation in Fig. 4.4(a), same as in Fig. 4.3(d), are compared with an equivalent spherical calculation in Fig. 4.4(b). Apparently, there are no symmetric or asymmetric fission structures in Fig. 4.4(b) for the spherical considerations.

Fig. 4.5 shows the results of our DCM calculated ER, fission, and qf cross-sections for all the four reactions, compared with experimental σ_{ER} and $\sigma_{fiss.}$ data [13,14]. The DCM calculated σ_{ER} fit the data very nicely for all the four cases at all the reported energies. Also, the DCM calculated $\sigma_{fiss.}$ show a good fit to data, except at one or two highest energy points. Specifically, the fission data at the

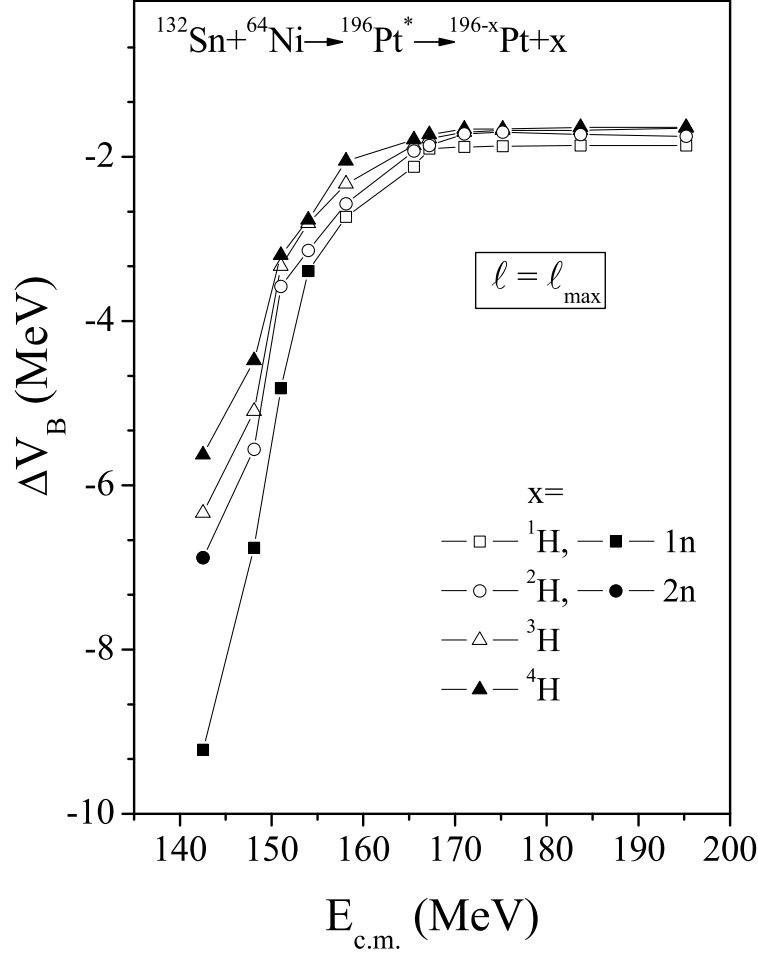


Figure 4.7 The barrier lowering parameter ΔV_B as a function of $E_{c.m.}$, calculated on DCM for the light particles emissions (ERs) at $\ell = \ell_{max}$ in the decay of $^{196}Pt^*$ formed in $^{132}Sn + ^{64}Ni$ reaction.

highest one energy for $^{176,182}Pt^*$, and at the highest two energies for $^{188,196}Pt^*$ could not be fitted to DCM calculated $\sigma_{fiss.}$. This called for the possible qf-contribution at these selected energies which let the calculated $\sigma_{fiss.} + \sigma_{qf}$ fit the data better. We notice in these figures and Tables 4.1-4.4 that the qf-contribution at the highest energy is rather large, in some cases (refer to $^{64}Ni + ^{124,132}Sn \rightarrow ^{188,196}Pt^*$) even larger or as much as the fission contribution. The interesting result is that the DCM calculated total fusion cross-section, including qf-contribution, i.e., $\sigma_{fusion} = \sigma_{ER} + \sigma_{fiss.} + \sigma_{qf}$, fits the data better than the earlier available one-dimensional barrier

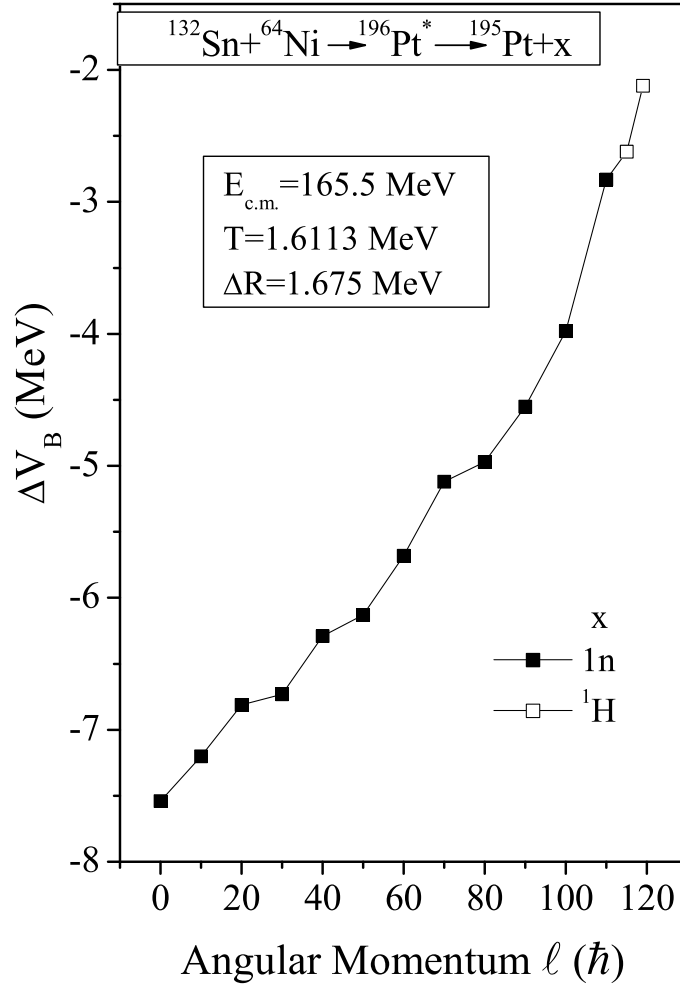


Figure 4.8 Same as for Fig. 4.7, but ΔV_B as a function of ℓ .

penetration model (BPM), CCFULL and density constrained TDHF (DC-TDHF) calculations [14]. This is shown explicitly in Fig. 4.6 for $^{132}\text{Sn} + ^{64}\text{Ni} \rightarrow ^{196}\text{Pt}^*$ reaction. Interestingly, for the DCM, it happens because of the inbuilt property of "barrier lowering" at sub-barrier energies, as is illustrated in Fig. 4.7 where the barrier lowering parameter ΔV_B is plotted as a function of $E_{\text{c.m.}}$ for the light particles involved in the evaporation residue (ER) of $^{132}\text{Sn} + ^{64}\text{Ni}$ reaction at $\ell = \ell_{\text{max}}$. The same result holds good at any other ℓ -value, as is evident from Fig. 4.8 showing the variation of ΔV_B with ℓ at one of the $E_{\text{c.m.}}$. In other words, the DCM calculations clearly stress the importance of the non-compound, quasi-fission content in fission

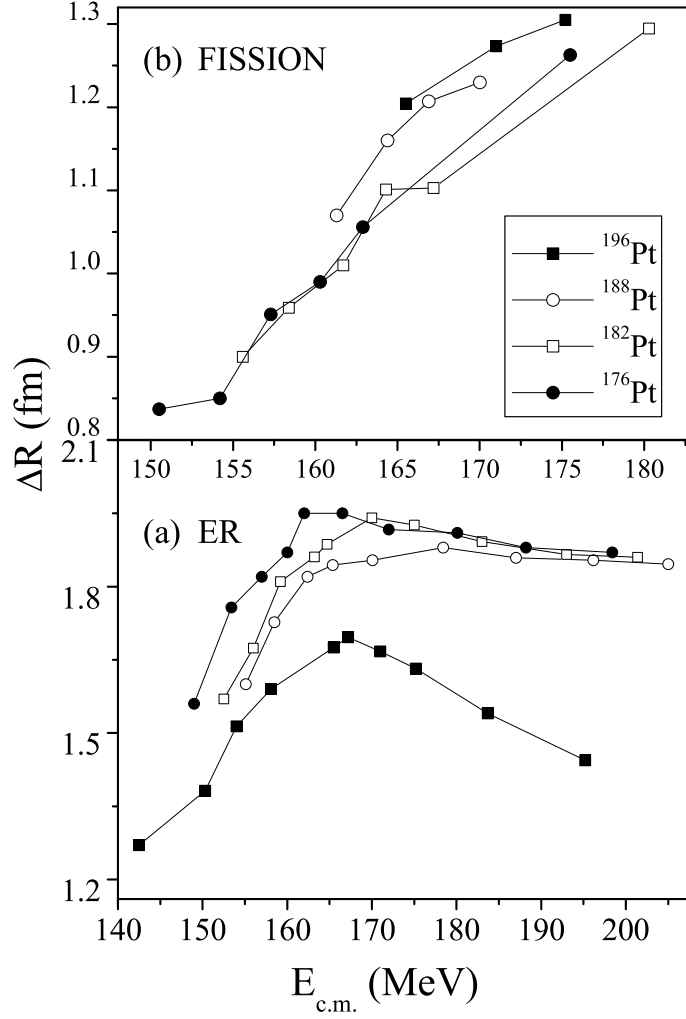


Figure 4.9 The best fitted neck-length parameter ΔR to ER and fission cross-section data in Fig. 4.5, plotted as function of $E_{c.m.}$, for $^{176,182,188,196}Pt^*$ nuclei.

cross-sections at above-barrier energies, and the need of barrier lowering effect in ER cross-sections at sub-barrier energies for a proper interpretation of fusion data for the ^{64}Ni induced reactions on stable $^{112,118,124}Sn$ or radioactive ^{132}Sn nuclei.

Fig. 4.9 shows the neck-length parameter ΔR , controlling the barrier-lowering parameter ΔV_B , for the best fit to ER and fission data in Fig. 4.5, plotted as a function of $E_{c.m.}$ for ER (Fig. 4.9(a)) and fission (Fig. 4.9(b)) processes in all the four reactions. We notice in Fig. 4.9(a) for ER that the ΔR -value decreases

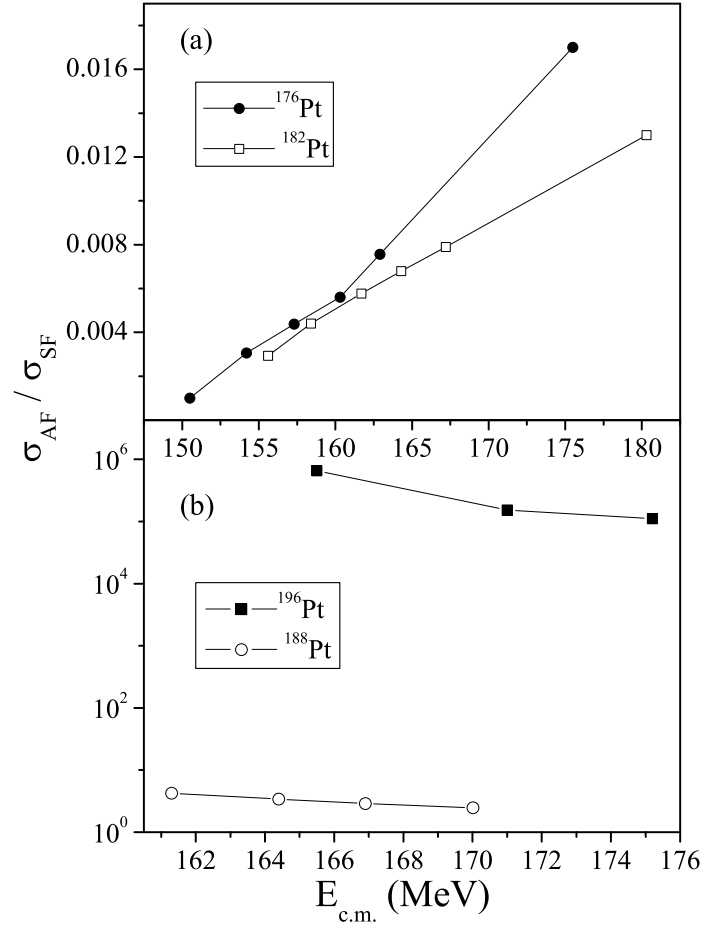


Figure 4.10 The AF-peak to SF-peak ratio plotted as a function of $E_{c.m.}$ for $^{176,182}\text{Pt}^*$ and $^{188,196}\text{Pt}^*$ systems.

almost systematically up to $^{188}\text{Pt}^*$ as the N/Z ratio of CN increases. However, the behaviour of ΔR versus $E_{c.m.}$ for $^{196}\text{Pt}^*$ is different, showing a sudden decrease in ΔR and a further decreasing trend of ΔR at higher $E_{c.m.}$'s, beyond 165 MeV. This peripheral nature (smaller ΔR) of $^{132}\text{Sn} + ^{64}\text{Ni} \rightarrow ^{196}\text{Pt}^*$ reaction is perhaps due to the sudden increase in number of neutrons in radioactive ^{132}Sn beam, and hence could be taken as the signatures of the iso-spin effect of larger N/Z ratio of CN. On the other hand, in Fig. 4.9(b) for the fission process, the two groups ($^{176,182}\text{Pt}^*$ and $^{188,196}\text{Pt}^*$) of symmetric and asymmetric fission (SF and AF) are clearly identified, with SF occurring at smaller ΔR values. Thus, the neck-length parameter ΔR

Table 4.1 The ER and fission cross-sections for $^{176}Pt^*$ systems, calculated on the DCM at different $E_{c.m.}$'s, compared with experimental data of $^{64}Ni+^{112}Sn$ reactions [13,14]. The quasi-fission (qf) contribution is also calculated. Here footnote [1] symbolizes quasi-fission (qf) contribution.

$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	σ_{ER} (mb) DCM Expt.	$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	$\sigma_{fission}$ (mb) DCM ($=\sigma_{SF}+\sigma_{AF}$)	Expt.
$^{64}Ni+^{112}Sn \rightarrow ^{176}Pt^* \rightarrow A_1 + A_2$										
198.4	1.9475	92	1.87	36.6 35	188.3	1.8081	94	1.44 1.118 ¹	326 (=320.4+5.6) 28.5 ¹	354.6
188.2	1.8067	91	1.88	39.3 39	175.5	1.6139	94	1.263	179 (=176+2.99)	179.7
180.1	1.91	89	1.91	43.8 43.4	162.9	1.396	92	1.056	18.136 (=18+0.136)	19
172	1.5565	87	1.917	43.5 43.6	160.3	1.3468	91	0.99	8 (=8+4.5 $\times 10^{-2}$)	8.3
166.5	1.4617	86	1.95	52.3 51.5	157.3	1.2874	91	0.951	5.4 (=5.4+2.3 $\times 10^{-2}$)	5.8
162	1.3793	85	1.95	49.8 49.7	154.2	1.223	90	0.85	0.98 (=0.98+3 $\times 10^{-3}$)	1
160	1.3409	86	1.87	26.3 27.3	150.5	1.1411	89	0.837	0.8 (=0.8+7.63 $\times 10^{-4}$)	0.8
157	1.2813	86	1.82	16.5 16.8						
153.4	1.2057	86	1.757	8.7 8.9						
149	1.1062	87	1.56	0.9 0.97						

clearly show the radioactive nature of the reaction in ER and that of SF versus AF in fission decay of $^{176,182,188,196}Pt^*$ nuclei in $^{64}Ni+^{112,118,124,132}Sn$ reactions.

Finally, for a further analysis of SF versus AF components in fission decay of Pt^* nuclei, in Figs. 4.10(a) and (b), we show the AF-peak to SF-peak ratio for the SF-dominant ($^{176,182}Pt^*$) and AF-dominant ($^{188,196}Pt^*$) nuclear systems, respectively. We notice in Fig.4.10(a) that the AF versus SF peak-ratio increases with the increase in $E_{c.m.}$ for the SF-dominant $^{176,182}Pt^*$ systems, whereas in Fig.4.10(b) the peak-ratio remains nearly constant for the AF-dominant $^{188,196}Pt^*$ systems. In other words, the asymmetric fission (AF) nature of decay in Pt^* nuclei becomes more and more prominent not only with the increase of iso-spin N/Z value, but also with the increase of $E_{c.m.}$. Thus, a fine- or sub-structure of fission process in Pt^* nuclei is

Table 4.2 The ER and fission cross-sections for $^{182}\text{Pt}^*$ systems, calculated on the DCM at different $E_{c.m.}$'s, compared with experimental data of $^{64}\text{Ni}+^{118}\text{Sn}$ reactions [13,14]. The quasi-fission (qf) contribution is also calculated. Here footnote [1] symbolizes quasi-fission (qf) contribution.

$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	σ_{ER} (mb)		$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	$\sigma_{fission}$ (mb)	
				DCM	Expt.					DCM ($=\sigma_{SF}+\sigma_{AF}$)	Expt.
$^{64}\text{Ni}+^{118}\text{Sn}\rightarrow^{182}\text{Pt}^*\rightarrow A_1+A_2$											
201.4	1.994	99	1.86	79	78	193.1	1.887	101	1.495	351.1 ($=341+10.1$)	394
									1.14 ¹	42.8 ¹	
193	1.8856	97	1.866	79.7	79.5	180.3	1.7084	99	1.2945	215 ($=212.23+2.77$)	214.5
183	1.7476	95	1.892	89.3	90	167.2	1.5036	98	1.103	28.22 ($=28+0.22$)	28.1
175	1.6287	94	1.926	108.6	108.7	164.3	1.4543	97	1.101	26.18 ($=26+0.18$)	26.4
170	1.5497	93	1.941	116	116.6	161.7	1.4086	97	1.01	8.5 ($=8.5+4.9\times 10^{-2}$)	8.8
164.7	1.4612	93	1.887	77	77.8	158.4	1.3483	97	0.959	4.5 ($=4.5+2\times 10^{-2}$)	4
163.2	1.4351	93	1.861	63	63.7	155.6	1.2949	97	0.9	1.2 ($=1.2+3.52\times 10^{-3}$)	1.2
159.2	1.3631	93	1.81	40.8	40.5						
156	1.3027	94	1.674	13.4	13.6						
152.5	1.233	93	1.57	3.6	3.7						

evident in Fig. 4.10.

4.3 Summary

We have studied the decay of CN $^{176,182,188,196}\text{Pt}^*$, formed via $^{64}\text{Ni}+^{112,118,124}\text{Sn}$ and $^{132}\text{Sn}+^{64}\text{Ni}$ reactions at near and sub-barrier energies, using the DCM where the quadrupole deformations (β_{2i}) and optimum orientations (θ_i^{opt}) of hot (compact) configurations play an important role. We observe that different isotopes of Pt^* display different decay patterns. With the increase in number of neutrons, i.e., with the increase of N/Z ratio of CN, the characteristics of the emitted light particles (the ER) change and the fission mass distribution changes from a symmetric to

Table 4.3 The ER and fission cross-sections for $^{188}Pt^*$ systems, calculated on the DCM at different $E_{c.m.}$'s, compared with experimental data of $^{64}Ni+^{124}Sn$ reactions [13,14]. The quasi-fission (qf) contribution is also calculated. Here footnote [1] symbolizes quasi-fission (qf) contribution.

$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	σ_{ER} (mb) DCM Expt.	$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	$\sigma_{fission}$ (mb) DCM ($=\sigma_{SF}+\sigma_{AF}$) Expt.
$^{64}Ni+^{124}Sn \rightarrow ^{188}Pt^* \rightarrow A_1 + A_2$									
205	2.0741	111	1.846	199.2	199.34	195.5	1.9601	113	1.41 153 (=71.3+81.7) 457.5 1.263 ¹ 305 ¹
196.17	1.9683	109	1.854	209	208.4	183.6	1.807	111	1.41 161.4 (=70.9+90.5) 272 1.177 ¹ 112 ¹
187.04	1.8525	108	1.859	215	215.4	170.01	1.614	109	1.23 40.6 (=11.7+28.9) 40.3
178.44	1.7362	106	1.88	237	235.9	166.9	1.5665	108	1.207 30 (=7.7+22.3) 30
170.01	1.614	106	1.854	197.1	197.6	164.4	1.5272	108	1.16 18 (=4.1+13.9) 18.6
165.38	1.5427	104	1.844	183	182.06	161.3	1.477	108	1.07 2.35 (=0.448+1.9) 2.8
162.4	1.495	103	1.82	151.8	151.8				
158.5	1.4301	104	1.727	75.7	75.4				
155.1	1.3701	104	1.6	24	24				

an asymmetric one. Specifically, for the neutron-rich, radioactive ^{132}Sn beam, the additional eight neutrons seems to be responsible for the neck-length parameter to be much smaller in $^{132}Sn+^{64}Ni$ reaction, more so at higher energies, thereby indicating a different reaction-time scale for this reaction. On the other hand, for the fission process, as a result of the deformations and orientations of fragments, the lighter two systems $^{176,182}Pt^*$ are predominantly of the symmetric fission nature, whereas for the heavier two systems $^{188,196}Pt^*$ the asymmetric fission dominates. In other words, with increasing iso-spin ratio N/Z of CN, not only the reaction-time scale changes but also a sub-or fine-structure of fission mass distributions is evident.

The DCM gives a nice description of both the ER and fission cross-sections, except that the fission cross-sections show the contribution of qf at the highest one

Table 4.4 The ER and fission cross-sections for $^{196}\text{Pt}^*$ systems, calculated on the DCM at different $E_{c.m.}$'s, compared with experimental data of $^{132}\text{Sn}+^{64}\text{Ni}$ reactions [13, 14]. The quasi-fission (qf) contribution is also calculated. Here footnote [1] symbolizes quasi-fission (qf) contribution.

$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	σ_{ER} (mb)		$E_{c.m.}$ (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	$\sigma_{fission}$ (mb)	
				DCM	Expt.					DCM ($=\sigma_{SF}+\sigma_{AF}$)	Expt.
$^{132}\text{Sn}+^{64}\text{Ni}\rightarrow^{196}\text{Pt}^*\rightarrow A_1+A_2$											
195.2	1.9944	122	1.446	260	259	195.2	1.9944	125	1.5	298 ($=3.04\times 10^{-3}+298$)	544
									1.204 ¹	244 ¹	
183.7	1.8556	122	1.5401	250	251.4	183.7	1.8556	122	1.5	315 ($=2.92\times 10^{-3}+315$)	371
									1.085 ¹	55 ¹	
175.2	1.7458	119	1.632	264.8	264.8	175.2	1.7458	120	1.305	234 ($=2.12\times 10^{-3}+234$)	232.9
171	1.6889	119	1.667	217	218	171	1.6889	120	1.2734	137 ($=8.95\times 10^{-4}+137$)	138
167.2	1.6357	117	1.696	233.5	234	165.5	1.6113	119	1.2045	31.7 ($=4.83\times 10^{-5}+31.7$)	31.2
165.5	1.6113	119	1.675	183	184						
158.1	1.5004	116	1.59	69.1	70						
154	1.4353	116	1.514	31.1	31.5						
151	1.3856	116	1.382	5.4	5 $\pm$ 1						
148.1	1.3359	116	1.25	0.7	0.7 $\pm$ 0.2						
142.5	1.234	115	1.194	0.078	>0.08						

energy for the lighter two isotopes $^{176,182}\text{Pt}^*$ and at the highest two energies in the heaviest $^{188,196}\text{Pt}^*$ cases. Thus, the total fusion cross-sections ($=\sigma_{ER}+(\sigma_{fiss.}+\sigma_{qf})$) calculated on DCM fit the data nicely for all the four isotopes of Pt^* over a wide range of energies. Specifically, other model calculations, like the BPM, CCFULL and DC-TDHF, are available for the $^{132}\text{Sn}+^{64}\text{Ni}\rightarrow^{196}\text{Pt}$ reaction and the DCM results are better than these predictions, in particular at sub-barrier energies. For DCM, this happens because of its inbuilt property of barrier lowering at sub-barrier energies. Thus, a non-compound, qf component in fission cross-sections at above-barrier energies, and the lowering-of-barriers for ER cross-sections at sub-barrier energies are clearly the essential requirements in DCM for a proper description of

the fusion data in ^{64}Ni based reactions on both stable $^{112,118,124}Sn$ and radioactive ^{132}Sn nuclei, similar to that in other $^{58,64}Ni + ^{58,64}Ni$ and $^{64}Ni + ^{100}Mo$ reaction.

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Chapter 5

Decay of $^{213,217}\text{Fr}^*$ systems formed in $^{19}\text{F}+^{194,198}\text{Pt}$ reactions

5.1 Introduction

The dynamical cluster-decay model is used for the first time to study the odd-mass nuclear systems $^{213}\text{Fr}^*$ (with $N=126$) and $^{217}\text{Fr}^*$ (with $N=130$) formed in $^{19}\text{F}+^{194,198}\text{Pt}$ reactions. Fission fragment angular distributions and fission anisotropies, together with fission excitation functions, i.e., fission cross-section σ_{fiss} as a function of center-of-mass energy $E_{c.m.}$ or compound nucleus (CN) excitation energy E_{CN}^* , are measured for the $^{19}\text{F}+^{194,198}\text{Pt}$ reactions forming compound systems $^{213,217}\text{Fr}^*$ [1]. As expected, σ_{fiss} for the more fissile $^{213}\text{Fr}^*$ is significantly larger over the entire measured energy range as compared to that for the less fissile $^{217}\text{Fr}^*$. Also, a significant contribution from the evaporation residue cross-section σ_{ER} is measured for both the systems at some of the energies (three of total six), which for $^{213}\text{Fr}^*$ is relatively small compared to σ_{fiss} at all measured energies, but

exceeds σ_{fiss} for $^{217}\text{Fr}^*$, except at the highest energy where σ_{fiss} supersedes σ_{ER} . Comparison of this data with the statistical saddle-point model (SSPM) [2] calculations [1] shows that, for a nice fit to the measured σ_{fiss} and σ_{ER} cross-sections, the anisotropy data for $^{217}\text{Fr}^*$ (with neutron number $N=130$) are in good accord with the SSPM over the entire energy range, except at the highest energy, but for $^{213}\text{Fr}^*$ (with $N=126$) show noticeable deviations from SSPM calculations at a few energies. On the other hand, in another recent experiment [3,4], similar measurements for the decay of CN $^{246}\text{Bk}^*$ show the entrance channel effects of the anisotropy of $^{11}\text{B}+^{235}\text{U}$ channel being consistent but that of $^{14}\text{N}+^{232}\text{Th}$ channel anomalous w.r.t. the SSPM, which were taken to imply the presence of a non-compound nucleus (nCN) reaction mechanism [5]. Very recently, B.B. Singh *et.al* in [6] showed the possibility of such a nCN component as the quasi-fission (qf) contribution in the fission cross-section of $^{246}\text{Bk}^*$ due to the incoming channel $^{11}\text{B}+^{235}\text{U}$, in contradiction with the measured anisotropy effects which indicate $^{14}\text{N}+^{232}\text{Th}$ channel to contain the nCN contribution. Note that $^{246}\text{Bk}^*$ is highly fissile and decays almost totally by fission (only σ_{fiss} is measured). Thus, the noted deviation in some measured anisotropy data from SSPM predictions seem to indicate either the shell closure property of CN or the presence of nCN, qf component at those energies.

In this chapter, we look for both the possibilities of the role of magic neutron shell ($N=126$) of the CN and the qf contribution, if any, on the basis of the dynamical cluster-decay model (DCM) of Gupta and collaborators [6–14], used first for the above mentioned decay study of $^{246}\text{Bk}^*$ [6] in the context of nCN, qf component. The difference between the $^{213,217}\text{Fr}^*$ and $^{246}\text{Bk}^*$ data lies in that here the evaporation residue cross-sections σ_{ER} are also measured. We have carried out our

calculations for spherical and β_2 deformed fragments, with "optimal" orientations of hot (compact) configurations [15]. Interesting feature of present study is that the experimental data can be fitted with either of possible choices i.e. spherical or β_2 deformed fragmentation and hence it provides an ideal case to look for the explicit role of deformations in the decay pattern of $^{213;217}\text{Fr}^*$ nuclei. Note that the DCM is applied here for the first time to odd mass fissioning nuclear systems $^{213;217}\text{Fr}^*$ with significant σ_{ER} contribution.

The calculations and discussions are elaborated in section 5.2 and the results are summarized in section 5.3.

5.2 Calculations

The decay of compound nuclei $^{213,217}\text{Fr}^*$ are studied at six center-of-mass (c.m.) energies $E_{c.m.}$ varying from 80 to 94 MeV, where experimental data are available [1]. Figs. 5.1(a, b) show the fragmentation potentials, for the decay of $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ at one each of the incident c.m. energies such that the two compound nuclei formed have the same excitation energy E_{CN}^* (~ 49 MeV). For investigating the comparative behavior of $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$, it is essential to keep the excitation energy same. Two cases of the fragments being spherical and β_2 -deformed are considered using "optimum" orientations θ_i^{opt} of hot configurations taken from Table 1 of [15]. The R_a (equivalently, ΔR) values for the LPs and fission region (consisting of IMFs, HMFs, nSF and SF) are required by data to take different values, varied simultaneously in order to fit both the σ_{ER} and σ_{fiss} data. ℓ_{max} corresponds to that value of angular momentum at which evaporation residue cross-sections become negligible

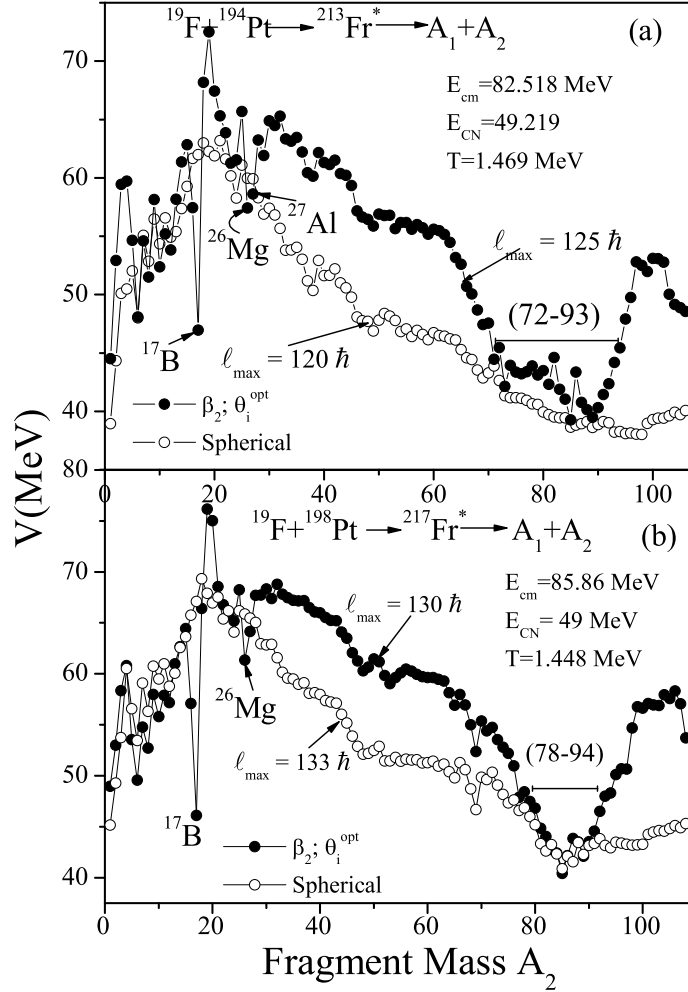


Figure 5.1 Fragmentation potential as a function of fragment mass number A_2 for the decay of compound systems $^{213,217}\text{Fr}^*$, plotted for the $\ell_{\max}$ -value, for both the cases of spherical and deformed nuclei.

i.e. $\sigma_{ER}(\ell) \rightarrow 0$.

First of all, we notice in Fig. 5.1(a, b) that the fragmentation potentials are relatively smooth for the spherical case, whereas the same show many new deep minima for β_2 deformed fragments. Besides this the fission distribution pattern changes from near symmetric to asymmetric fragmentation with inclusion of β_2 -deformation. Note that the lighter mass region of evaporation residue ($A_2=1-4$) is nearly independent of shape considerations of nuclei for $^{213}\text{Fr}^*$ whereas a noticeable deviation is seen in case of $^{217}\text{Fr}^*$.

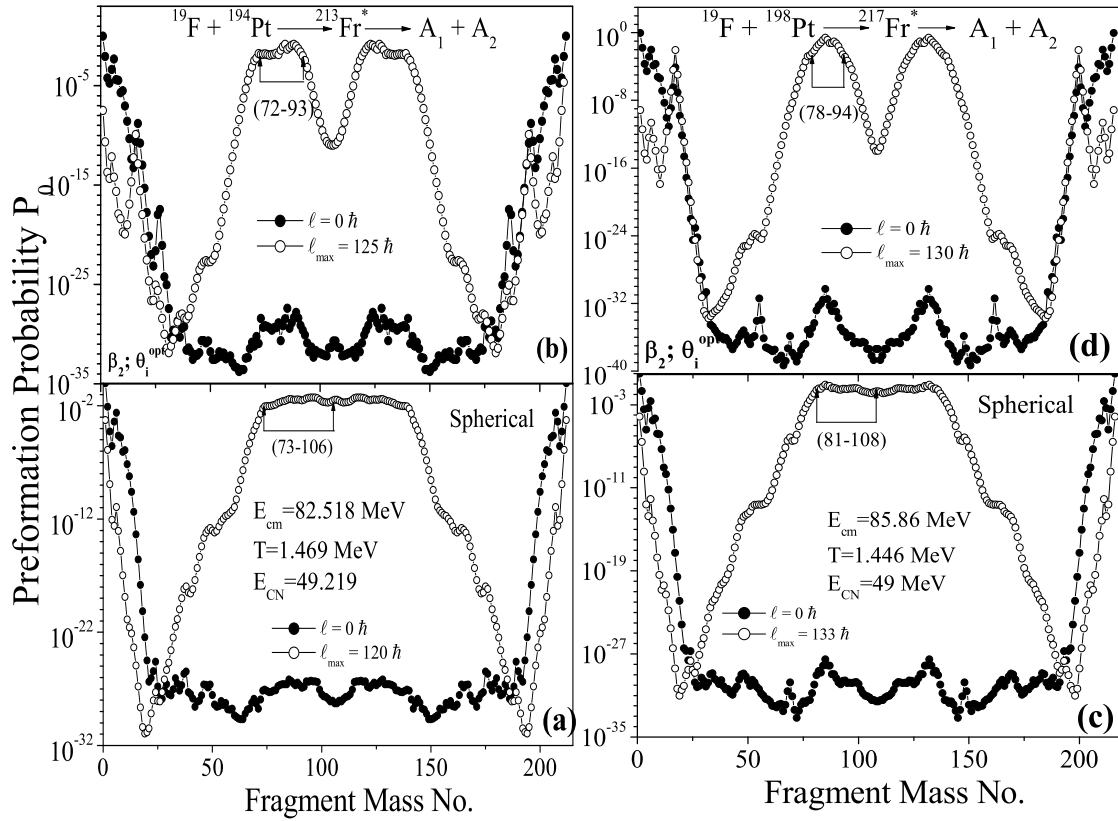


Figure 5.2 Preformation probability as a function of fragment mass no (A_2), for the decay of $^{213,217}\text{Fr}^*$ taking spherical, and (β_2) deformation effects and orientation.

Specifically in Fig.5.1(a,b), in addition to some very deep minima in the light mass region, there is only one mass region $A_2=72-93$ of asymmetric fission or near symmetric fission (nSF) valleys for $^{213}\text{Fr}^*$, whereas the same for $^{217}\text{Fr}^*$ also has one mass region $A_2=78-94$ of asymmetric fission (or nSF) within quadrupole deformation case. The deeper minima at $A_2=17, 26, 27$ do not affect the total cross-section as these get ruled out due to very small penetrability P shown in Fig. 5.3.

The above results of fission valleys are more vividly understood in Fig. 5.2 where the preformation probability P_0 is plotted as a function of the fragmentation

mass, at two extreme ℓ -values, $\ell=0$ and ℓ_{max} , for both the spherical and deformed considerations. For deformed calculations "optimal" orientations are included within hot (compact) configurations. Apparently, we observe that the distribution yields for $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ are nearly identical for spherical and β_2 deformed cases, except for different mass regions. The mass fragmentation is clearly symmetric for the spherical case and asymmetric for β_2 deformed case for $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ decays. The two distributions may be said different in that there is a slight hump in mass fragmentation of $^{213}\text{Fr}^*$ (N=126 case) whereas nSF window in case of $^{217}\text{Fr}^*$ is almost gaussian. However, it seems that contribution of β_2 -alone is perhaps not enough to establish the explicit role of N=126 in decay of $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ and hence it may be of interest to include higher multipole deformation effects in these calculations. The specific role of angular momentum can also be accessed from the variation of Preformation probability for $\ell=0$ and $\ell=\ell_{max}$ cases. It may be noticed that the light particles/clusters are more prominent at lower ℓ values and the heavier fragments are symmetric/asymmetric start competing with light particles with increase in ℓ and eventually at $\ell=\ell_{max}$ the heavy fragment formation probability supersedes that of lighter ones.

Fig.5.3 (a,b) shows the Penetration probability for $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ for spherical and β_2 deformations. It may be noticed that in both Fig.5.3(a) and (b) the penetration probability is extremely small for prominently preformed clusters ^{17}B , ^{26}Mg and ^{27}Al .

Fig. 5.4, and Tables 5.1 and 5.2, show the comparison of DCM calculations, based on β_2 deformed considerations, with experimental data [1] for ER and fission cross-sections of $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ compound systems. The deduced variation of

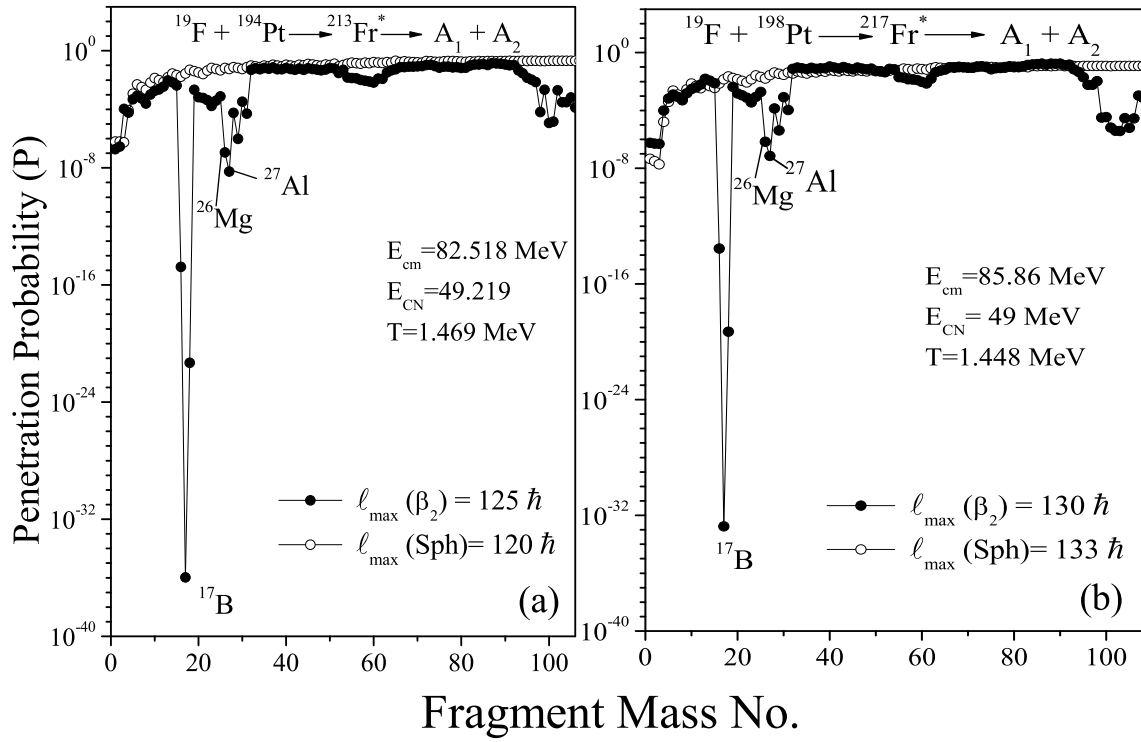


Figure 5.3 Penetration Probability as a function of fragment mass no (A_2), for the decay of $^{213,217}\text{Fr}^*$ taking spherical, and (β_2) deformation effects and orientation.

the neck-length parameter ΔR as a function of $E_{c.m.}$ for both the ER and fission processes in the two systems is shown in Fig. 5.5 for β_2 choice. Note that σ_{ER} is measured at only three of the six $E_{c.m.}$'s, and hence, for the remaining three energies, the ΔR values are obtained by extrapolating the calculated values for the measured ER cross-sections. We notice from Fig. 5.4 and Tables 5.1 and 5.2 that for both the compound systems we get an almost exact fit with the experimental data on both ER and fission cross-sections, using the deformations β_2 and "optimum" orientations θ^{opt} in DCM. Such a near exact comparison between the calculations and data for both the systems leaves no scope for the quasi-fission (qf) component in either of the two σ_{fiss} data. This result is in agreement with recent measurements of mass angle correlations and fission fragment angular distributions in other two reactions

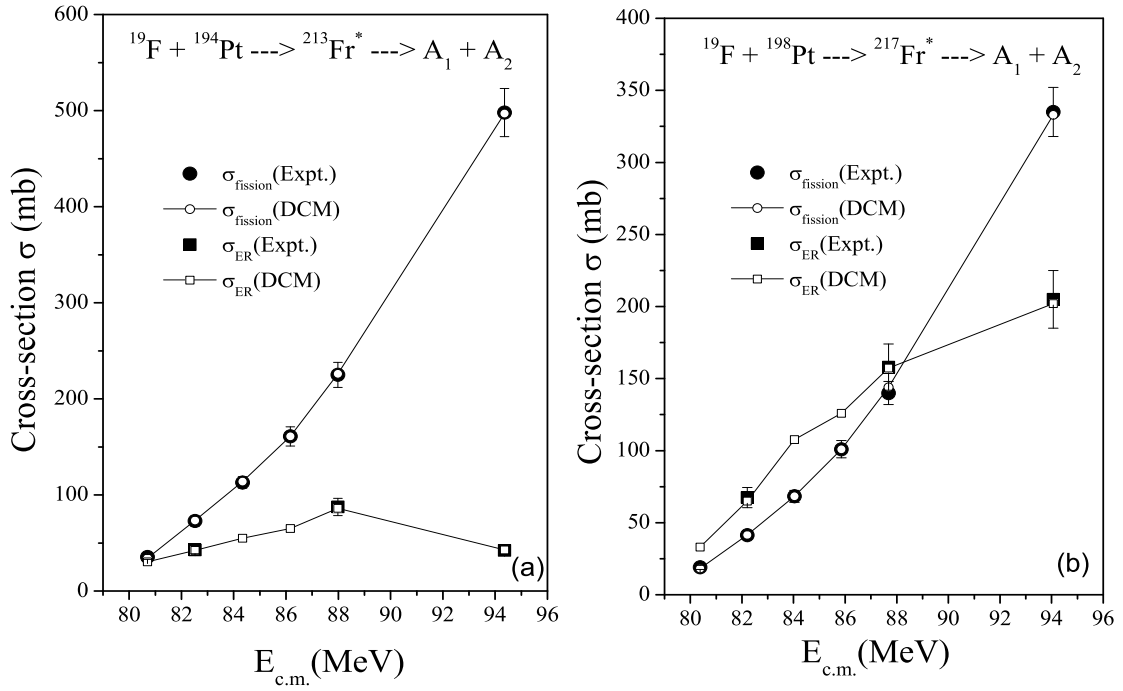


Figure 5.4 Comparisons between the experimental [1] and DCM calculated ER and fission cross-sections using deformed considerations for $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$ systems.

$^{16}\text{O} + ^{197}\text{Au}$ and $^{27}\text{Al} + ^{186}\text{W}$ [16] forming the same compound system $^{213}\text{Fr}^*$, showing no evidence of nCN, qf component in these decays.

Fig 5.5, showing the variation of fitted parameter ΔR as a function of $E_{c.m.}$ for both the ER and fission processes in $^{213,217}\text{Fr}^*$ systems, also contain interesting information. First of all, we observe that ER is a prompt process since ΔR for this process is large for both the systems, more so for the less fissile $^{217}\text{Fr}^*$ in the β_2 choice of fragmentation. The less fissile nature of $^{217}\text{Fr}^*$, compared to $^{213}\text{Fr}^*$, is also evident here for its ΔR for fission process being smaller compared to that for $^{213}\text{Fr}^*$.

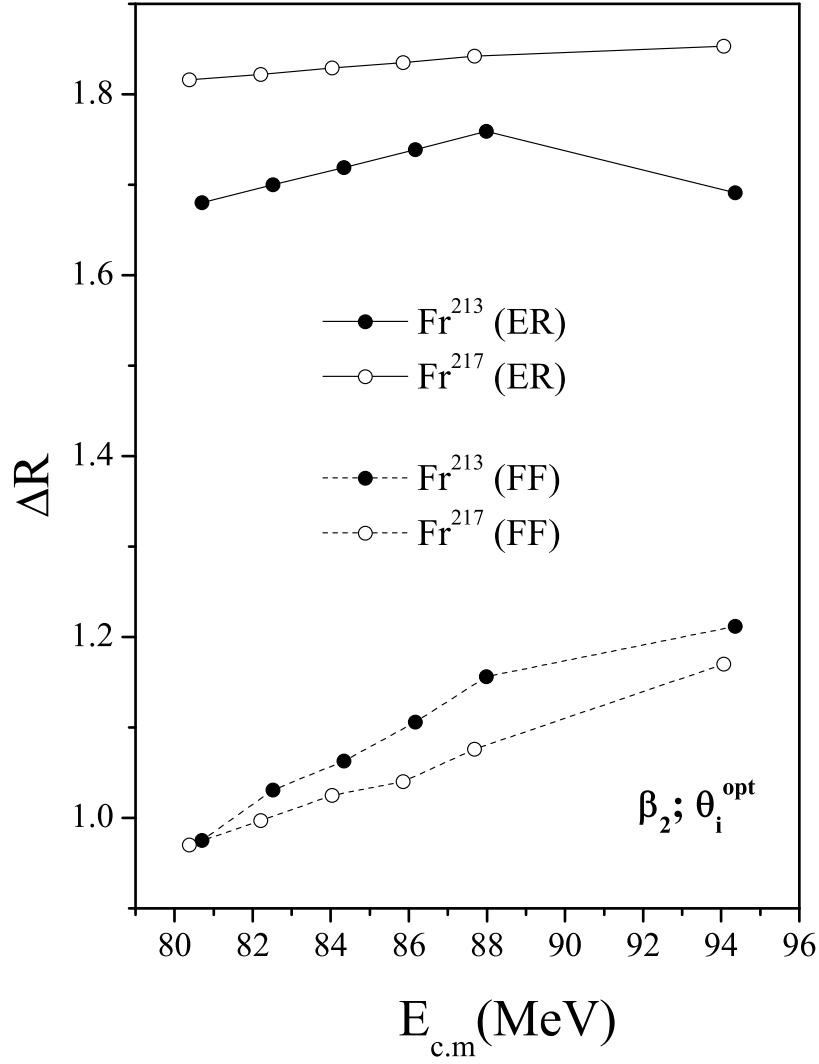


Figure 5.5 The variation of fitted parameter ΔR with $E_{c.m.}$ for ER and fission processes in decaying $^{213,217}\text{Fr}^*$ systems in the (a) β_2 deformation, (b) β_2 - β_4 deformation.

5.3 Summary

We have studied the decay of odd-mass nuclear systems $^{213}\text{Fr}^*$ (with $N=126$) and $^{217}\text{Fr}^*$ (with $N=130$) formed in $^{19}\text{F}+^{194,198}\text{Pt}$ reactions, using for the first time the dynamical cluster-decay model (DCM) with quadrupole (β_2) deformations having "optimal" orientations of hot (compact) configurations. Comparisons are also made with the calculations for spherical considerations. In DCM, both the measured evap-

Table 5.1 The ER and fission cross-sections for different $E_{c.m.}$, calculated on DCM using deformed and "optimum" oriented fragments, and compared with experimental data [1] for $^{19}\text{F} + ^{194}\text{Pt} \rightarrow ^{213}\text{Fr}^*$ reaction. The ER consists of $A_2 \leq 4$ ($=x$ neutrons, $x=1-4$) and the fission window of asymmetric mass valley $A_2=73-97$, plus complementary fragments.

$E_{c.m.}$ (MeV)	E_{CN} (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR_{fiss} (fm)	σ_{fiss}		σ_{ER}		
					DCM (mb)	Expt. (mb)	ΔR_{ER} (fm)	DCM (mb)	Expt. (mb)
80.697	47.397	1.4364	124	0.9752	34.1	35.5 ± 2.5	1.68	30.4	$\longleftrightarrow$
82.518	49.219	1.469	125	1.031	73.3	72.8 ± 5.1	1.7	42.3	42.8 ± 4
84.34	51.041	1.4899	126	1.063	114	113 ± 6	1.719	54.9	$\longleftrightarrow$
86.162	52.862	1.5158	126	1.106	161	161 ± 10	1.739	65.1	$\longleftrightarrow$
87.983	54.684	1.5414	126	1.156	226	225 ± 13	1.759	86.2	87.5 ± 9
94.359	61.059	1.6275	128	1.212	497	498 ± 25	1.691	42.8	42.3 ± 5

oration residue (ER) and fission cross-sections are treated on equal footing, where fission consists of intermediate and heavy mass fragments, the asymmetric or near-symmetric, and symmetric fission fragments. The anomalous fission anisotropies measured for $N=126$ $^{213}\text{Fr}^*$ system, which are normal for the $N=130$ $^{217}\text{Fr}^*$ system, are considered to be associated with either the neutron magic shell of the compound nucleus or a presence of nCN, qf component in the measured fission cross-sections. Both the role of magic neutron shell and the possibility of qf component in σ_{fiss} are investigated within the DCM. In order to look for the possible role of neutron shell closure effects of the compound nucleus, calculations are made at the same compound nucleus excitation energy for both the systems.

Interestingly, for the case of quadrupole deformed and "optimum" oriented fragments, the near exact comparison between the calculated and experimental σ_{fiss} data (as well as the σ_{ER} data) for both the compound systems leaves no possibil-

Table 5.2 Same as for Table 1, but for $^{19}\text{F}+^{198}\text{Pt}\rightarrow^{217}\text{Fr}^*$ reaction, with fission window consisting of asymmetric+symmetric mass valleys $A_2=80-91$ and 104-108, plus complementary fragments.

$E_{c.m.}$ (MeV)	E_{CN} (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR_{fiss} (fm)	σ_{fiss}		σ_{ER}		
					DCM (mb)	Expt. (mb)	ΔR_{ER} (fm)	DCM (mb)	Expt. (mb)
80.382	43.479	1.3767	127	0.97	18.3	19 ± 1.5	1.816	33.1	$\longleftrightarrow$
82.207	45.303	1.3916	128	0.997	41.6	41.4 ± 3	1.822	65	67.5 ± 7
84.032	47.128	1.4189	128	1.025	68.3	68.3 ± 4.1	1.829	107.6	$\longleftrightarrow$
85.857	48.953	1.4458	130	1.04	101	101 ± 6	1.835	125.9	$\longleftrightarrow$
87.682	50.778	1.4721	130	1.0759	144	140 ± 8	1.842	157.3	158 ± 16
94.069	57.165	1.5607	132	1.1702	333	335 ± 17	1.853	202	205 ± 20

ity of the quasi-fission component in the fission cross-section of either of the two systems. The β_2 deformed choice don't indicate the expected N=126 shell closure effect although a little lump is seen in case of $^{213}\text{Fr}^*$ (N=126) decay as compared to $^{217}\text{Fr}^*$ (N=130) mass fragmentation. It will be of further interest to include the higher multipole deformations and "generalized orientation" in the decay process of these nuclei in order to look further the role of N=126 in the decay of $^{213}\text{Fr}^*$ nucleus. Besides this, the mass fragmentation process changes from symmetric to asymmetric with the inclusion of β_2 -deformation in $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$.

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Chapter 6

Role of deformations in Cluster Radioactivity

6.1 Introduction

The cluster radioactivity has been studied quite extensively during last three decades in order to investigate the spontaneous decay of Francium, Radium and the actinide nuclear systems. The cluster radioactivity (or cluster decay) is a type of nuclear disintegration in which a radioactive nuclei emit clusters of neutrons and protons heavier than the alpha particle. This type of decay happens only in nuclide which decay predominantly by alpha decay, and occurs in a fractional percentage as compared to alpha decay process. The emission of clusters heavier than α -particles is not being accompanied by any neutron emission. Thus, it is a cold process (zero excitation energy) where the energy released in the form of Q-value is completely consumed by the kinetic energy alone of the two fragments (the cluster and daughter nuclei). The clusters usually emitted in this process are the neutron rich isotopes

of carbon, nitrogen, oxygen, fluorine, neon, magnesium and silicon. The concept of cluster radioactivity is limited to heavy nuclei which have enough nuclear energy, the Q-value ($Q > 0$), to expel a portion of its nucleons. The emitted cluster has an intermediate position between alpha decay and spontaneous fission (in which a heavy nucleus splits into two comparable fragments).

After its theoretical discovery in 1980 by Săndulescu, Poenaru and Greiner [1] cluster decay was discovered in 1984 when researchers at Oxford University detected that ^{223}Ra emits one ^{14}C nucleus for every billion (10^9) alpha decays [2]. Since then, emissions of many other clusters e.g., ^{15}N , $^{18,20}\text{O}$, ^{23}F , $^{22,24,25,26}\text{Ne}$, $^{28,30}\text{Mg}$ and $^{32,34}\text{Si}$, have been observed from about 20 heavy nuclear systems in mass region $A = 220\text{--}248$. The kinematics of the emitted clusters, initially, indicated that the lighter member of a daughter pair i.e. cluster is emitted in its ground state. However, more refined measurements ultimately revealed that in one case, the cluster member of a daughter pair can also be emitted in an excited state e.g., ^{14}C in the spontaneous decay of ^{223}Ra [2]. The cluster radioactivity is so far confined mostly to actinide nuclei like the isotopes of Actinium, Thorium, Protactinium, Uranium, Neptunium, Plutonium, Americium and Cerium etc. Beside this ^{14}C and ^{15}N clusters have been emitted in isotopes of Francium and Radium. Some work has been done on theoretical as well as experimental front [3] to look for the possibility of cluster emission in lighter nuclei in mass $A \sim 114$ but nothing conclusive could be established as yet. The exploration of the CR in the super-heavy region did not receive much attention possibly because of their short half life.

The existing theoretical models which have been used to investigate this rare decay phenomena can be divided into two categories: the Unified Fission Model

(UFM) [4] and the Preformed Cluster Model (PCM) [5]- [9]. Although the presumptions of UFM and the PCM are completely different but both seem to be working nicely in order to understand the spontaneous cluster-decay process. The UFM considers cluster radioactivity simply as a barrier penetration phenomenon in between the fission and the α -decay without worrying about the cluster being or not being preformed in the parent nucleus. On the other hand, in PCM the clusters are assumed to be preborn in a parent nucleus before they could penetrate the potential barrier with a given Q -value. The basic assumption of the UFM is that heavy clusters as well as the α -particle have equal probability of being preformed. In PCM, clusters of different sizes have different probabilities of their being preformed in the parent nucleus. With in the fission models of cluster radioactivity, the ground-state deformation effects of the parent and/or daughter, keeping the emitted cluster still spherical, were introduced by Shanmugam and Kamalaharan [10] for the finite-range Yukawa-plus-exponential potential, and for the emitted quadrupole deformed cluster, treating the daughter as spherical, by Gupta et al. [11,12] using the double folded Michigan-3 Yukawa (M3Y) potential. The deformation effects of the daughter nucleus, as well as the higher multipole deformations, were also accounted for later with in the M3Y potential [13]. In this chapter, we have studied the deformation and orientation effects of the parent as well as that of decay products i.e. daughter and cluster, with in PCM [14,15] .

Here we have investigated the role of deformations and orientations of decaying nucleus and emitted fragment(s) in the ground state decay of parent nuclei, using Preformed Cluster Model (PCM) of Gupta and collaborators. The deformation and orientation effects are investigated for all measured clusters including

the recent experimental cases of ^{14}C and ^{15}N decays from ^{223}Ac and ^{34}Si emitted from ^{238}U [16, 17]. In order to establish the explicit role of deformation, the ground state decay calculations are done for spherical, quadrupole deformed (β_2), and higher multipole deformations ($\beta_2, \beta_3, \beta_4$) fragmentation. As the fragmentation potential, preformation probability and penetration probability of emitted clusters get influenced by the use of deformation and orientation effects, so the inclusion of such effects seems extremely desirable in order to establish the clustering phenomena. Through our calculations, we have concluded that in CR the deformation and orientation effects are almost indispensable, just like Q-value and shell effects. The calculated decay half lives for cluster decays investigated are generally in good agreement with measured data for calculations performed with quadrupole deformations β_2 alone and optimum orientation of cold elongated configuration [18]. In some cases, however, particularly for observed ^{14}C decay of Ra and Ac nuclei, the inclusion of multi-pole deformations up to hexadecapole β_4 is found essential for comparison with data. It may be noted that the measured β_4 values are not available in general and hence the available data should be used carefully in order to avoid misinterpretation.

The calculations and results pertaining to the role of deformation and orientation in CR are discussed in Section 5.2. Finally the results are summarized in section 5.3.

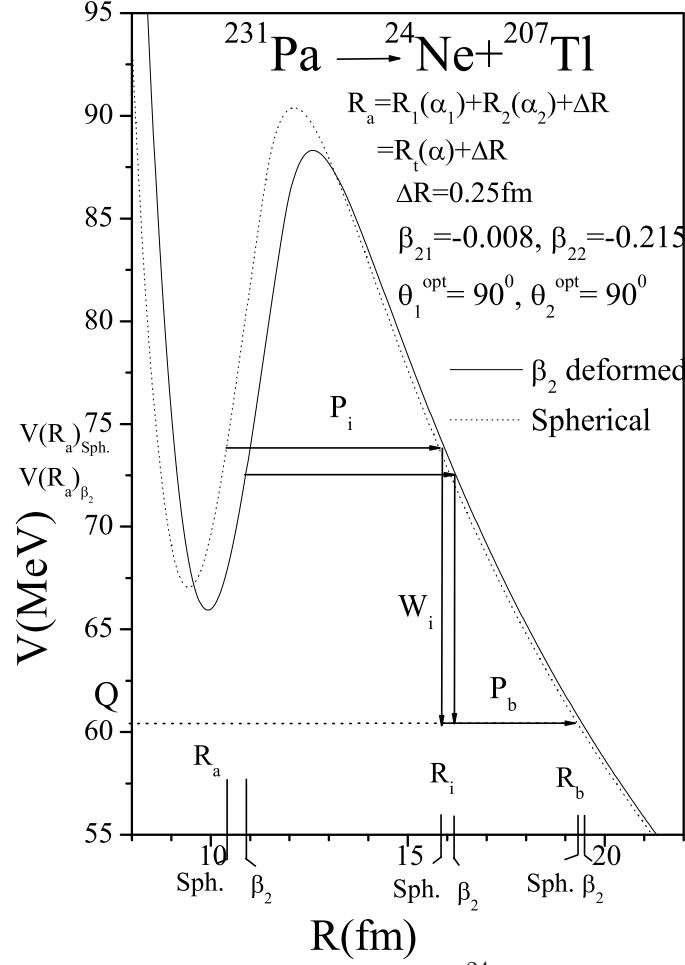


Figure 6.1 The scattering potentials for the ^{24}Ne cluster decay of parent nucleus ^{231}Pa , i.e., $^{231}\text{Pa} \rightarrow ^{24}\text{Ne} + ^{207}\text{Tl}$, for ^{24}Ne considered as a spherical and deformed nucleus with "optimum" cold orientation angles θ_i^{opt} of Table I in Ref. [18].

6.2 Calculations

The preformed cluster model (PCM) of Gupta and collaborators [5]- [9], with effects of deformations and orientations degrees of freedom included, is based on the well-known quantum mechanical fragmentation theory (QMFT) [18]- [20]. The scattering potentials in Fig. 5.1., plotted for spherical and deformed considerations, show that the barrier position as well as height get modified with the inclusion of deformation and orientation effects of the ^{24}Ne cluster. Due to deformations, the barrier height

gets reduced and position increased, thereby affecting the tunnelling penetrability P (also see Fig.1 in [14] where decay of $^{232}\text{U} \rightarrow ^{208}\text{Pb} + ^{24}\text{Ne}$ shows similar behavior). Note from Eq.(2.57) that the calculated decay constant λ (or half-life $T_{1/2}$) depends on Penetration probability P , and hence on inclusion/ or non-inclusion of deformations and orientations of nuclei. In Fig. 5.1., the transmission probability P consists of the following three contributions [5], [7]:

- (i) The penetrability P_i from R_a to R_i ,
- (ii) the (inner) de-excitation probability W_i at R_i , and
- (iii) the penetrability P_b from R_i to R_b

giving the penetration probability as $P = P_i W_i P_b$.

Here we are interested only in the ground-state solution ($T = 0$). R_a is the first turning point of the penetration path used for calculating the penetrability P , illustrated in Fig. 6.1 for $^{231}\text{Pa} \rightarrow ^{207}\text{Tl} + ^{24}\text{Ne}$. We note in Fig. 6.1. (and Table 6.2.) that the first turning point $R_a \geq R_t$, where R_t is the touching configuration. This means to say that, in the present cluster decay calculations, the potential V ($R < R_a$) does not come in to play, and hence the shell effects for inside the barrier are not very significant, although these could very well be calculated on, say, the two-center shell model [8].

Figure 6.2 (a, b) illustrates the fragmentation potentials $V(\eta)$ of ^{223}Ac and ^{238}U parent nuclei at $R = R_a$, for both the cases of all fragments taken as spheres (open circles) and with quadrupole deformation β_2 and optimum orientations (solid circles). The value of R_a (equivalently, the neck-length parameter ΔR) is for the best fit to the data in Table 6.2. The important point to note in Fig. 6.2 is that, with deformation and orientation effects included, many new minima are predicted

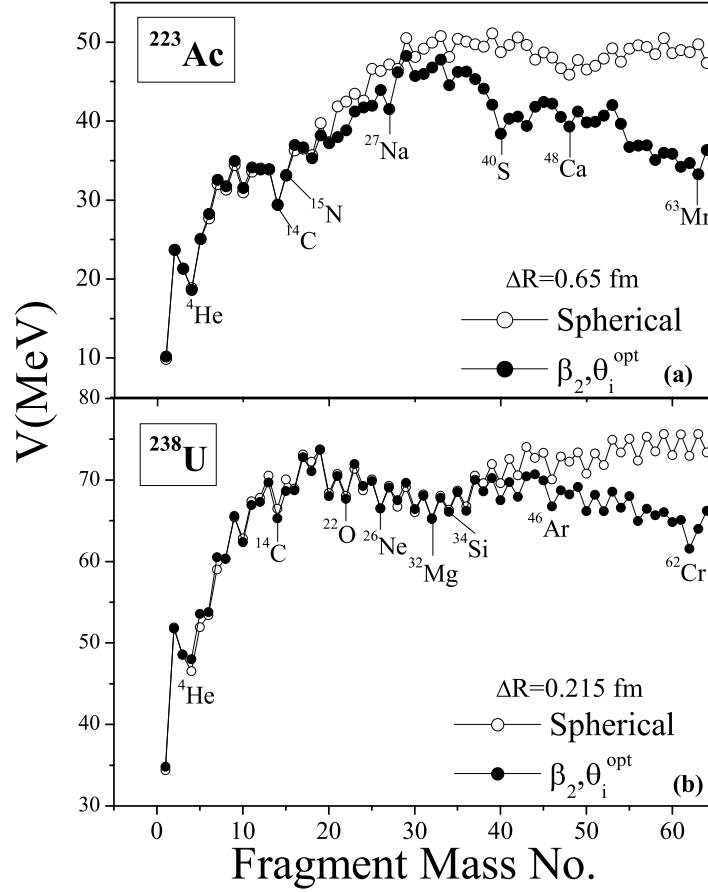


Figure 6.2 The fragmentation potentials for the parent nuclei ^{223}Ac and ^{238}U , taking all possible fragments as spheres (open circles) and with quadrupole deformation β_2 and cold "optimum" orientations θ_i^{opt} of Table 1 in Ref. [18] (solid circles) at the best fitted ΔR values.

in ^{223}Ac for cluster mass $A_2 > 25$, and in ^{238}U for $A_2 > 40$. The change in Potential energy surfaces (PES) are observed even for lighter clusters as shown in Fig. 6.3. The case of higher multi-pole deformations ($\beta_2, \beta_3, \beta_4$) is not plotted here because it leads to deeper minima for many unobserved clusters like in Fig. 6.6 (b). The role of higher multi-pole deformations is explained in Fig. 6.6 (b) and Fig. 6.7 for ^{14}C decay, where inclusion of such effects seems essential in reference to reported experimental data.

In Fig 6.3 Preformation probability is plotted as a function of cluster mass for

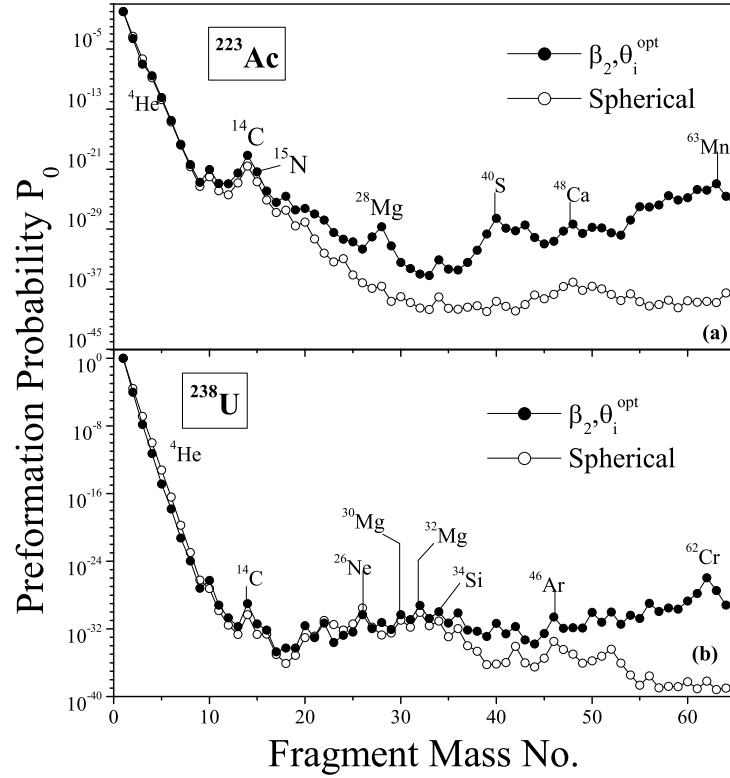


Figure 6.3 Same as for Fig. 5.2 but for the preformation probability, P_0 , and for ^{223}Ac and ^{238}U .

the decay of ^{223}Ac and ^{238}U . Here we observe that the preformation probabilities are, in general, larger for the case of deformations and orientations included for both the cases i.e. ^{223}Ac and ^{238}U . In Fig.6.3(a) preformation probability for ^{14}C and ^{15}N clusters is evident in ^{223}Ac decay. The study of ^{223}Ac decay is interesting for the odd-even effects of both daughter and cluster, which were earlier observed for a few cases only, like ^{14}C from ^{221}Fr and ^{225}Ac or ^{23}F from ^{231}Pa . Although ^{15}N decay of ^{223}Ac is expected to be more favored, because the daughter nucleus is doubly magic ^{208}Pb nucleus in this case, but only the upper limits are measured. Similarly for ^{238}U parent, ^{34}Si is the heaviest cluster measured till date but with the longest half life ever measured. We notice in Fig. 6.3 (b) that the preformation factor P_0 for clusters like ^{26}Ne , ^{30}Mg , and ^{32}Mg are as large as for the observed

Table 6.1 The cluster-decay half-lives for some best preformed clusters in the neighborhood of ^{34}Si from ^{238}U , calculated on PCM of Gupta et al. [5], [7], [8] by using the Q values ($Q_{M.N.}$) based on binding energies from Moller et al. [22]. The experimental data is known only for ^{34}Si decay of ^{238}U [17].

Decay	Q-value (MeV)		Half-life ($T_{1/2}$) s		
			PCM		Expt.
	$Q_{A.W.}$	$Q_{M.N.}$	β_2	Sph.	
$^{238}\text{U} \rightarrow ^4\text{He} + ^{234}\text{Th}$	4.27	4.26	5.27×10^{23}	3.80×10^{24}	1.41×10^{17}
$^{238}\text{U} \rightarrow ^{24}\text{Ne} + ^{214}\text{Pb}$	53.44	53.34	1.35×10^{39}	4.14×10^{40}	-
$^{238}\text{U} \rightarrow ^{26}\text{Ne} + ^{212}\text{Pb}$	54.43	54.14	1.83×10^{37}	1.74×10^{38}	-
$^{238}\text{U} \rightarrow ^{30}\text{Mg} + ^{208}\text{Hg}$	69.28	70.90	1.18×10^{31}	6.56×10^{32}	-
$^{238}\text{U} \rightarrow ^{32}\text{Mg} + ^{206}\text{Hg}$	69.06	70.39	9.90×10^{31}	1.26×10^{33}	-
$^{238}\text{U} \rightarrow ^{34}\text{Si} + ^{204}\text{Pt}$	84.65	85.82	1.09×10^{29}	2.36×10^{30}	$(1.1 \pm_{0.6}^{2.4}) \times 10^{29}$

cluster ^{34}Si . However, we shall see in the following (refer to Table 6.1) that all these clusters (other than ^{34}Si) get ruled out due to their smaller penetrability P or large calculated decay half-life times.

The role of penetrability P in choosing the right cluster in PCM calculations is indicated in Table 6.1 where the decay half-life times [$T_{1/2}(\text{s})$] are calculated for four clusters (^{26}Ne , ^{30}Mg , ^{32}Mg , and ^{34}Si) preformed in ^{238}U with larger preformation factors P_0 in the neighborhood of the observed ^{34}Si cluster (see Fig. 6.3). Both the cases of spherical and quadrupole deformed nuclei are considered. Interestingly, although the preformation probability P_0 for, say, ^{32}Mg is larger than for ^{34}Si (see Fig. 6.3) or the minimum in fragmentation potential is deeper for ^{32}Mg as compared to that for ^{34}Si (see Fig. 6.2, lower panel), the decay half-life time is the smallest for the ^{34}Si decay for ^{238}U , in complete agreement with the experimental data for the case of quadrupole deformed nuclei. This happens because the penetrability P for ^{32}Mg is much smaller than for ^{34}Si such that the product $P_0 P$ is smaller, and hence $T_{1/2}(\text{s})$ larger.

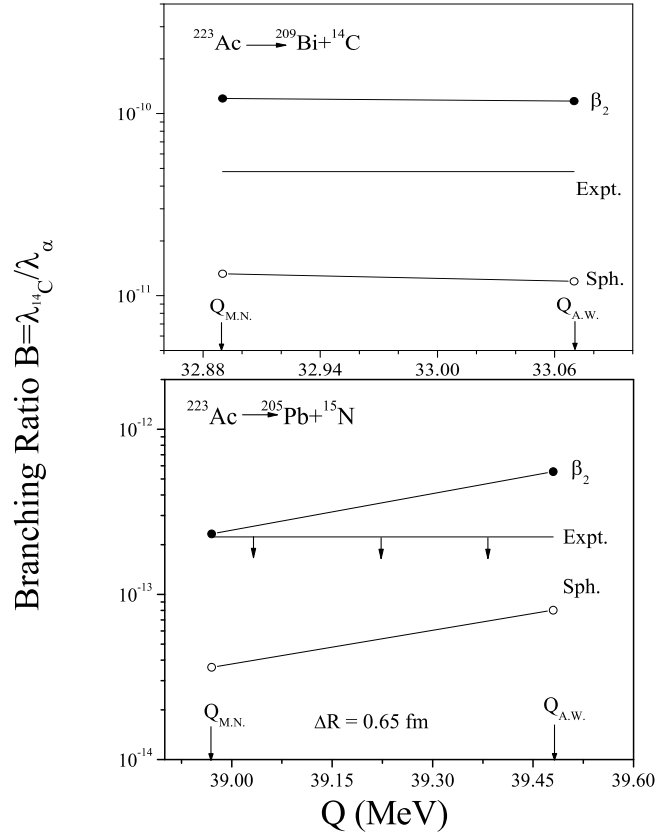


Figure 6.4 Comparison between the experimentally observed and calculated branching ratios for the ^{14}C and ^{15}N clusters emitted from the ^{223}Ac , as a function of the Q value. The measured upper limit for ^{15}N decay of ^{223}Ac in the lower panel is shown by down arrows. The $Q_{M.N.}$ and $Q_{A.W.}$ refer, respectively, to Q values calculated by using the binding energies from Moller et al. [22] and Audi and Wapstra [21].

Figures 6.4 and 6.5 depict the comparison of experimentally observed and our calculated branching ratios $B (= \lambda_{\text{cluster}} / \lambda_{\alpha})$ for ^{14}C and ^{15}N clusters emitted from ^{223}Ac and half-life time $T_{1/2}(\text{s})$ for ^{34}Si emitted from ^{238}U parent nuclei, as a function of Q value, for both the cases of nuclei taken as spherical or with β_2 deformation. Apparently, the calculated branching ratio for ^{14}C cluster from ^{223}Ac show very little dependence on Q value, and the experimental value lies in between the values predicted for nuclei considered spherical or quadrupole deformed. This result indicates that the inclusion of higher multipoles is perhaps essential for ^{14}C cluster

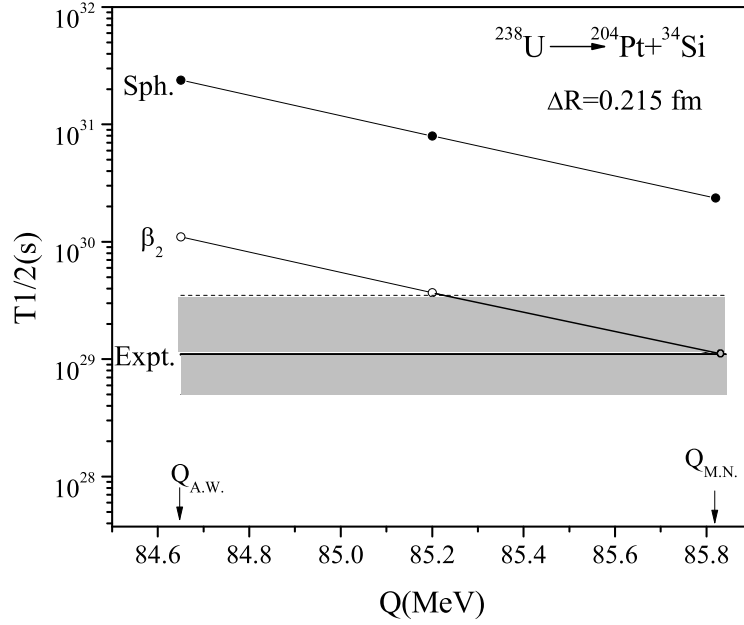


Figure 6.5 Same as for Fig. 5.3 (b) but for ^{34}Si cluster emitted from the ^{238}U and for half-life time instead of branching ratio.

decay. However, both ^{15}N decay of ^{223}Ac and ^{34}Si decay of ^{238}U parents show a clear preference for the case of quadrupole deformed nuclei. The only parameter of model is the neck-length ΔR , fitted for $Q_{M.N.}$, the Q value based on binding energies of Moller et al. [22]. We also show in Figs. 6.4 and 6.5 that the Q value ($Q_{A.W.}$) calculated from Audi-Wapstra table of binding energies [21], show large differences with $Q_{M.N.}$ values. As Q -value of a reaction plays proactive role in deciding the decay process of emitted clusters and daughters so half-life and Q -value should be measured in same set of experiment.

We have extended the above calculations based on the PCM to all the parent nuclei where cluster decays are observed [23], or upper limits on decay half-life times obtained [23], for use of spherical, quadrupole deformation (β_2) alone, and, wherever possible, the higher multipole deformations ($\beta_2, \beta_3, \beta_4$) of both the daughter and cluster nuclei with optimum orientations $\theta_i^{opt.}$ of cold elongated configurations from Table 1 of Ref. [18]. The results of these calculations are given in Table 6.2, compared

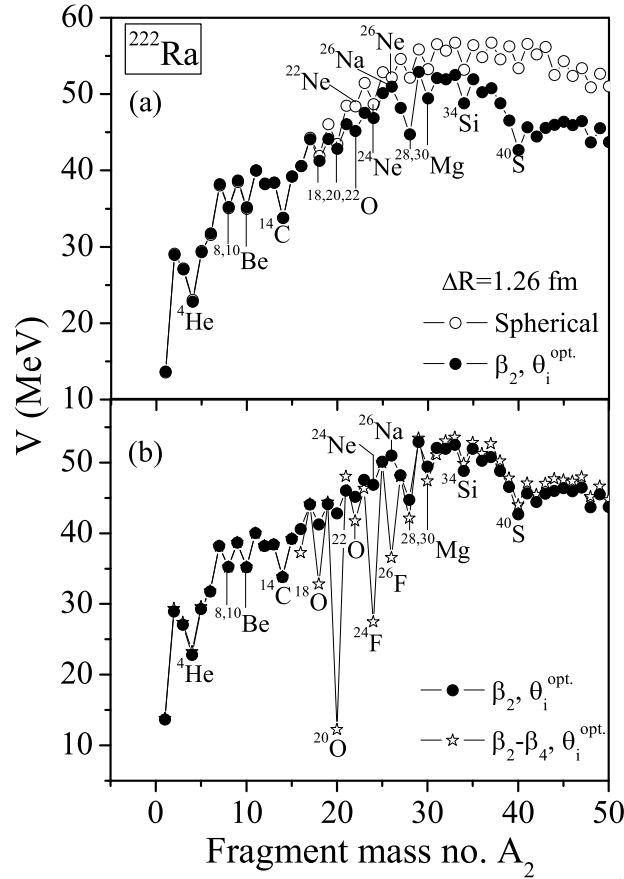


Figure 6.6 The fragmentation potentials for parent nuclei ^{222}Ra , for cases of (a) spherical compared with quadrupole deformation β_2 alone, and (b) quadrupole deformation β_2 alone compared with quadrupole plus octupole plus hexadecapole deformations ($\beta_2\text{-}\beta_4$), taken into account for all possible fragments. The orientation angles are the "optimum" cold $\theta_i^{\text{opt.}}$ of Table I in Ref. [18].

with the experimental data [23]- [25] clearly show that the majority of data (except for ^{14}C) can be fitted with the choice of quadrupole deformations (β_2 alone) with optimum orientations. The only exceptions are ^{25}Ne and ^{28}Mg decays of ^{234}U and ^{30}Mg emitted from ^{238}Pu , where spherical considerations seem to do better. Also, ^{34}Si decay of ^{242}Cm via ^{208}Pb daughter gives a better result for spherical nuclei because both the cluster and daughter are spherical nuclei. The calculated half-lives are limited to $\log_{10}T_{1/2}(\text{s}) < 30$, which excludes from Table 6.2 the $^{24,26}\text{Ne}$ decays of ^{232}Th and $^{235,236}\text{U}$ parents. The cluster-decay process is shown to occur, in general,

at or near the touching configuration (ΔR is zero or small).

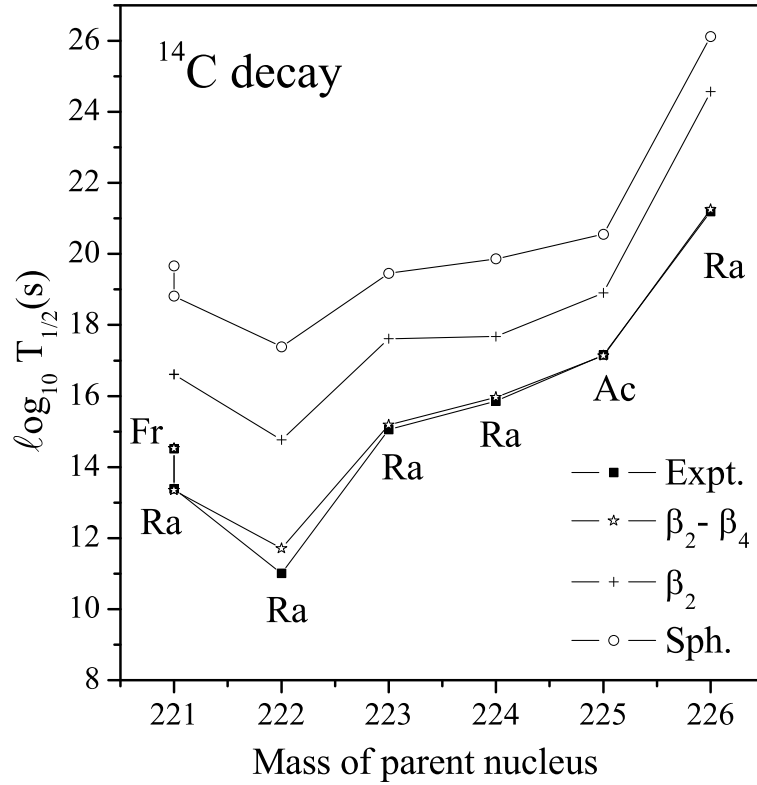


Figure 6.7 Comparison between the experimentally observed and calculated decay half-lives for ^{14}C cluster emitted from various Ra isotopes and ^{221}Fr and ^{225}Ac parent nuclei in the ground state.

For ^{14}C clusters formed in ^{221}Fr , $^{221-224,226}\text{Ra}$, and ^{225}Ac parents, apparently, higher multipole deformations up to β_4 are found to be important for comparisons with data. The role of higher multipoles is depicted in Fig. 6.6, and we observe that for ^{222}Ra parent, there is no change in PES for the cluster mass up to $A_2 = 15$. For $A_2 > 15$, many new minima are observed in going from spherical to deformed (β_2 alone or $\beta_2 - \beta_4$). In Fig 6.6, new minima at ^{28}Mg and ^{40}S are obtained in going from spherical to β_2 alone, and in the case of including higher multipole deformations (β_2 , β_3 , β_4), many new clusters, like $^{16,18,20}\text{O}$, $^{24,26}\text{F}$, and ^{40}S are favored, which are not experimentally observed, and also get ruled out in calculations because of their small penetrability P . However, the relative preformation factor P_0 changes considerably,

even for lighter clusters of masses $A_2 \leq 15$. This is illustrated in Table I [14], where both P_0 and P are given for the three cases of spherical, β_2 alone, and $(\beta_2, \beta_3, \beta_4)$, for some of measured clusters.

Figure 6.7 and Table II [14] show the comparison between the experimentally observed cluster decay half-lives and the calculations based on the PCM for the three cases of spherical, quadrupole deformation β_2 alone, and quadrupole, octupole, hexadecapole deformations $(\beta_2, \beta_3, \text{ and } \beta_4)$, and "optimum" orientations for ^{14}C decay. Figure 6.7, for ^{14}C cluster decay from different Ra isotopes and that from ^{221}Fr and ^{225}Ac shows clearly that the comparison between the data and calculations is the best for all considered decays when higher multipole deformations $(\beta_2, \beta_3, \text{ and } \beta_4)$ are included. It will be of interest to investigate the explicit role of higher multipole deformations using generalized orientation in exotic ^{14}C cluster radioactivity as an future endeavor.

6.3 Summary

We have investigated the role of deformation and orientation of the decaying parent nucleus and of emitted fragment(s) in the ground-state decay of the daughter nucleus, using the preformed cluster model (PCM) of Gupta and collaborators. The interesting point is that both the preformation factor P_0 and penetrability P are shown to get modified with the inclusion of deformation and orientation effects. Moreover, unlike P , the P_0 is affected not only due to the shapes of parent, daughter and cluster nuclei, but also due to the shapes of all other possible fragmentation of the decaying parent nucleus.

We have studied the role of deformation and orientation for all measured clusters including the very recent experiments [16,17] of ^{14}C and ^{15}N decays from ^{223}Ac and ^{34}Si emitted from ^{238}U . We consider here the cluster radioactive decays where both the daughter and cluster are spherical and or deformed and orientated. We find that β_2 alone is good enough to fit the experimental data, whereas the inclusion of higher multi-pole deformations either show an anomalous behavior or the observed cluster is not an obvious choice because it is either not energetically favored (not at the minimum in the calculated fragmentation potential) or excluded by the penetrability factor. However higher multi-pole deformation effects seem essential for ^{14}C decay. In conclusion, the role of deformations and orientations is extremely desirable as that of shell effects and Q-value. It is so because, both the mass fragmentation and scattering potentials, and hence the cluster preformation and barrier penetration factors get modified due to inclusion of deformation and orientation effects.

Table 6.2 Half-life times and other characteristic quantities for cluster decays of various parent nuclei. The calculations are made for use of the PCM of Gupta and collaborators [5], [6], [7], [8], for cases of spherical, β_2 alone and $(\beta_2, \beta_3$ and $\beta_3)$ deformed nuclei, and "optimum" orientations of cold decay process [18]. The impinging frequency $\nu_0 \sim 10^{21} s^{-1}$, fixed for each case. $Q_{M.N.}$ refers to Q value calculated by using the binding energies of Möller *et al.* [22]. In view of the presently measured cluster-decay half-lives, the calculated values are limited to $\log_{10}T_{1/2}(s) < 30$.

Decay	Half-lives $\log_{10}T_{1/2}$					
	R_a	$Q_{M.N.}$	β_2	PCM $\beta_2, \beta_3, \beta_4$	Sph.	Expt.
$^{114}\text{Ba} \rightarrow ^{12}\text{C} + ^{102}\text{Sn}$	$R_t + 1.7$	21.4	6.89	6.83	5.43	>4.10
$^{221}\text{Fr} \rightarrow ^{14}\text{C} + ^{207}\text{Tl}$	R_t	30.55	16.62	14.53	19.66	14.52
$^{221}\text{Ra} \rightarrow ^{14}\text{C} + ^{207}\text{Pb}$	R_t	32.13	16.61	13.35	18.81	13.39
$^{222}\text{Ra} \rightarrow ^{14}\text{C} + ^{208}\text{Pb}$	$R_t + 1.26$	32.47	15.89	11.20	17.36	11.01
$^{223}\text{Ra} \rightarrow ^{14}\text{C} + ^{209}\text{Pb}$	R_t	31.89	17.61	15.19	19.45	15.06
$^{224}\text{Ra} \rightarrow ^{14}\text{C} + ^{210}\text{Pb}$	R_t	36.78	17.67	15.97	19.86	15.86
$^{226}\text{Ra} \rightarrow ^{14}\text{C} + ^{212}\text{Pb}$	R_t	28.61	24.57	21.25	26.12	21.29
$^{223}\text{Ac} \rightarrow ^{14}\text{C} + ^{209}\text{Bi}$	$R_t + 0.65$	32.89	12.02		12.98	12.60
$^{223}\text{Ac} \rightarrow ^{15}\text{N} + ^{208}\text{Pb}$	$R_t + 0.65$	38.97	14.73		15.54	>14.76
$^{225}\text{Ac} \rightarrow ^{14}\text{C} + ^{211}\text{Bi}$	R_t	31.08	18.9	17.14	20.55	17.16
$^{226}\text{Th} \rightarrow ^{14}\text{C} + ^{212}\text{Po}$	$R_t + 0.65$	31.70	19.56	24.34	20.9	> 15.3
$^{226}\text{Th} \rightarrow ^{18}\text{O} + ^{208}\text{Pb}$	$R_t + 0.65$	47.55	18.35		20.10	> 15.3
$^{228}\text{Th} \rightarrow ^{20}\text{O} + ^{208}\text{Pb}$	$R_t + 0.5$	45.91	20.40		21.72	20.87
$^{230}\text{Th} \rightarrow ^{24}\text{Ne} + ^{206}\text{Hg}$	$R_t + 0.5$	58.57	24.19		24.06	24.61
$^{231}\text{Pa} \rightarrow ^{23}\text{F} + ^{208}\text{Pb}$	$R_t + 0.25$	50.81	27.38	09.28	28.73	26.02
$^{231}\text{Pa} \rightarrow ^{24}\text{Ne} + ^{207}\text{Tl}$	$R_t + 0.25$	60.59	23.07		25.86	23.23
$^{230}\text{U} \rightarrow ^{22}\text{Ne} + ^{208}\text{Pb}$	R_t	61.69	19.41	01.27	26.15	19.57
$^{230}\text{U} \rightarrow ^{24}\text{Ne} + ^{206}\text{Pb}$	R_t	61.81	23.07		25.35	> 18.2
$^{232}\text{U} \rightarrow ^{24}\text{Ne} + ^{208}\text{Pb}$	R_t	62.03	22.88	11.19	24.04	21.05
$^{232}\text{U} \rightarrow ^{28}\text{Mg} + ^{204}\text{Hg}$	R_t	74.06	20.31	21.23	28.78	> 22.26
$^{233}\text{U} \rightarrow ^{24}\text{Ne} + ^{209}\text{Pb}$	$R_t + 0.5$	60.55	24.57		24.06	24.84
$^{233}\text{U} \rightarrow ^{28}\text{Mg} + ^{205}\text{Hg}$	$R_t + 0.5$	74.42	19.22	15.02	24.06	> 27.59
$^{234}\text{U} \rightarrow ^{24}\text{Ne} + ^{210}\text{Pb}$	$R_t + 0.5$	59.30	25.99		24.06	25.92
$^{234}\text{U} \rightarrow ^{25}\text{Ne} + ^{209}\text{Pb}$	$R_t + 0.5$	56.67	30.38		24.06	25.92
$^{234}\text{U} \rightarrow ^{26}\text{Ne} + ^{208}\text{Pb}$	$R_t + 0.5$	58.65	26.49	16.15	28.00	25.92
$^{234}\text{U} \rightarrow ^{28}\text{Mg} + ^{206}\text{Hg}$	$R_t + 0.5$	74.22	18.44	15.02	26.72	25.54
$^{235}\text{U} \rightarrow ^{28}\text{Mg} + ^{207}\text{Hg}$	R_t	72.62	26.19		30.08	> 28.09
$^{236}\text{U} \rightarrow ^{28}\text{Mg} + ^{208}\text{Hg}$	R_t	71.33	25.55		31.53	27.58
$^{238}\text{U} \rightarrow ^{34}\text{Si} + ^{204}\text{Pt}$	$R_t + 0.215$	85.82	29.04		30.37	29.04
$^{237}\text{Np} \rightarrow ^{30}\text{Mg} + ^{207}\text{Tl}$	R_t	75.18	26.44		28.12	> 26.93
$^{236}\text{Pu} \rightarrow ^{28}\text{Mg} + ^{208}\text{Pb}$	$R_t - 0.4$	78.75	21.57		28.7	21.67
$^{238}\text{Pu} \rightarrow ^{28}\text{Mg} + ^{210}\text{Pb}$	$R_t - 0.4$	75.83	25.40		33.7	25.70
$^{238}\text{Pu} \rightarrow ^{30}\text{Mg} + ^{208}\text{Pb}$	$R_t + 0.5$	76.82	21.87		24.77	25.70
$^{238}\text{Pu} \rightarrow ^{32}\text{Si} + ^{206}\text{Hg}$	$R_t + 0.5$	90.03	25.16			25.27
$^{241}\text{Am} \rightarrow ^{34}\text{Si} + ^{207}\text{Tl}$	R_t	93.62	22.83		25.23	> 21.66
$^{242}\text{Cm} \rightarrow ^{34}\text{Si} + ^{208}\text{Pb}$	R_t	95.78	21.47		23.59	23.24
$^{252}\text{Cf} \rightarrow ^{46}\text{Ar} + ^{206}\text{Hg}$	R_t	126.19	19.66	28.07	20.29	> 15.89
$^{252}\text{Cf} \rightarrow ^{48}\text{Ca} + ^{204}\text{Pt}$	R_t	138.33			21.56	> 15.89
$^{252}\text{Cf} \rightarrow ^{50}\text{Ca} + ^{202}\text{Pt}$	R_t	137.71	20.06		21.76	> 15.89

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Chapter 7

Summary and outlook

We have studied the competing decay modes of various excited and ground state nuclear systems in order to understand explicit role of angular momentum, nuclear deformations and orientations, etc. The reaction dynamics of hot and rotating nuclei in mass range $A \sim 200$ has been investigated and the issues related to shell effects, structure/ sub-structure of fission fragments, iso-spin effect, quasi-fission, etc., are addressed by using the Dynamical Cluster-decay Model (DCM) and Preformed Cluster Model (PCM). DCM is an extension of Preformed Cluster Model (PCM) which find its basis in Quantum Mechanical Fragmentation Theory (QMFT). Within this formulism, the fragmentation potential is calculated as sum of temperature dependent binding energies, Coulomb interaction, proximity potential and rotational energy. The main advantage of DCM over other available statistical models is that it treats the emission of light particles (LP's) and intermediate mass fragments (IMF's), and fission fragments on equal footings, whereas in other statistical models the LP's and IMF's and fission are treated differently. Another important feature of DCM is that it involves the preformation probability of fragments and hence im-

parts important nuclear structure information. The simple case of $\ell=0$, $T=0$ within DCM, the PCM accounts for ground state decays which can be used to investigate the cluster radioactivity and related phenomena.

An overview of current research status of fusion-fission and related aspects have been discussed in Chapter 1. Beside this a brief account of low energy nuclear reactions is explained where emphasis is made on deep understanding of compound nuclear systems. The inclusion of deformations and orientations changes the interaction barrier (its height as well as position) thereby affecting the dynamics of reaction process. It is relevant to mention here that a favorable compact shape results in a hot compound nucleus, than an elongated touching shape at the barrier. The compound nucleus (CN) is normally in an excited state depending upon the energy of reaction partners, it loses this excitation energy in various possible ways emitting ER, IMF, HMF, SF and QF etc. The role of angular momentum, excitation energy, together with the effects of deformed and oriented nuclei is quite significant. The roles of such effects are analyzed through various heavy ion reactions using Dynamical Cluster Decay Model. The details of DCM are given in Chapter 2.

As a first application of the Dynamical cluster decay model (DCM), in Chapter 3 we have studied the decay of $^{202}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction at different center-of-mass energies for spherical fragments. We find that the light-particles (fusion-evaporation residue) are favored at lower as well as higher angular momenta whereas the symmetric fragments (SF) $A = 81-101$ ($=A_{CN}/2 \pm 20$) together with near-symmetric fragments (nSF) $A = 65-75$ are favored more at higher angular mo-

menta. The interesting feature of this study is that the three decay processes (ER, FF and QF) are quite comparable at low energies, ER being the most dominant, whereas at higher energies fusion-fission (FF) becomes most probable followed by ER and QF. The competing non-CN, QF is considered not to lose its entrance channel identity, and its contribution is large w.r.t., say, FF in many reactions such as ^{48}Ca plus heavy actinides forming the superheavy elements with $Z = 112$, 114 and 116. Here we observe a window like structure which indicates a fine- or sub-structure in the fusion-fission of compound nucleus $^{202}\text{Pb}^*$. The ℓ -summed preformation probability P_0 shows an interesting nuclear structure information with significant preformation factor for light particles as well as for SF and nSF. The contribution of nSF window is quite significant, of the order of 20% for at least a few lower c.m. energies, and then decreases as energy increases, perhaps due to reduced shell effects at higher incident energies. The nSF window (responsible for QF process) is shown to be due to the presence of shell effects (magic shells) in the mass distributions, further supported by its absence (also, no QF decay channel) in the mass-fragmentation preformation yield calculations for the decay of compound nucleus $^{192}\text{Pb}^*$ formed in $^{48}\text{Ca} + ^{154}\text{Sm}$ reaction. The only parameter of the model is the neck-length ΔR which shows that the ER occurs first, having the largest values of ΔR , and the FF and QF processes occur almost simultaneously at lower incident energies but the FF takes over QF at higher incident energies. In other words, the three processes occur in different time scales, QF competing with FF at lower incident energies. The calculated ER, FF and QF cross-sections show excellent comparisons with the available experimental data.

In Chapter 4, we have studied the decay of Pt isotopes i.e. $^{176,182,188,196}\text{Pt}^*$ formed by $^{64}\text{Ni}+^{112}\text{Sn}$, $^{64}\text{Ni}+^{118}\text{Sn}$, $^{64}\text{Ni}+^{124}\text{Sn}$ and $^{132}\text{Sn} + ^{64}\text{Ni}$ reactions using DCM for the deformed fragments with quadrupole (β_2) deformations and optimal orientation for hot (compact) configuration where the data for evaporation residue (ER) and fission cross-section are available both near and below barrier. At sub-barrier energies, for all the four reactions, the ER cross-sections are measured to be larger than the corresponding fission cross-sections. In this case we observe that different isotopes of Pt^* display different decay patterns. With the increase in number of neutrons, i.e., with the increase of N/Z ratio of CN, the characteristics of the emitted light particles (the ER) change and the fission mass distribution changes from a symmetric to an asymmetric one. The lighter two systems $^{176,182}\text{Pt}^*$ are predominantly of the symmetric fission nature, whereas for the heavier two systems $^{188,196}\text{Pt}^*$ the asymmetric fission dominates. With increasing iso-spin ratio N/Z of CN, not only the reaction time scale changes but also a sub- or fine-structure of fission mass distributions is evident. The DCM gives a nice description of both the ER and fission cross-sections, except that the fission cross-sections show the contribution of qf at the highest one energy for the lighter two isotopes $^{176,182}\text{Pt}^*$ and at the highest two energies in the heaviest $^{188,196}\text{Pt}^*$ cases. Thus, the total fusion cross-sections ($=\sigma_{ER}+\sigma_{fiss.}+\sigma_{qf}$) calculated on DCM fit the data nicely for all the four isotopes of Pt^* over a wide range of energies. Specifically, other model calculations, like the BPM, CCFULL and DC-TDHF, are available for the $^{132}\text{Sn} + ^{64}\text{Ni} \rightarrow ^{196}\text{Pt}^*$ reaction and the DCM results are better than these predictions, in particular at sub-barrier energies. For DCM, this happens because of its inbuilt property of "barrier lowering" at sub-barrier energies. Thus, a non-compound, qf component in

fission cross-sections at above-barrier energies, and the lowering-of-barriers for ER cross-sections at sub-barrier energies are clearly the essential requirements in DCM for a proper description of the fusion data in ^{64}Ni based reactions on both stable $^{112,118,124}\text{Sn}$ and radioactive ^{132}Sn nuclei.

In Chapter 5, we have studied the decay of odd-mass nuclear systems $^{213}\text{Fr}^*$ (with $N=126$) and $^{217}\text{Fr}^*$ (with $N=130$) formed in $^{19}\text{F}+^{194,198}\text{Pt}$ reactions using DCM. The comparative behavior of fragmentation process is studied by taking spherical, quadrupole deformations (β_2) considerations in an "optimal" orientations of hot (compact) configurations. In this study the observed anomalous fission anisotropies measured for $N=126$ $^{213}\text{Fr}^*$ system, which are normal for the $N=130$ $^{217}\text{Fr}^*$ system, are considered to be associated with either the neutron magic shell of the compound nucleus or a presence of nCN, qf component in the measured fission cross-sections. Both the role of magic neutron shell and the possibility of qf component in σ_{fiss} are investigated on the DCM. In order to look for the possible role of neutron shell closure effects of the compound nucleus, calculations are made at the same compound nucleus excitation energy for both the systems. Interestingly, for the case of quadrupole deformed and optimum oriented fragments, the near exact comparison between the calculated and experimental σ_{fiss} data (as well as the σ_{ER} data) for both the compound systems leaves no possibility of the quasi-fission component in the fission cross-section of either of the two systems. The β_2 deformed choice don't indicate the expected $N=126$ shell closure effect although a little lump is seen in case of $^{213}\text{Fr}^*$ ($N=126$) decay as compared to $^{217}\text{Fr}^*$ ($N=130$) mass fragmentation. It will be of further interest to include the higher multipole deformations and "generalized

orientation” in the decay process of these nuclei in order to see the explicit role of $N=126$ in the decay of $^{213}\text{Fr}^*$ nucleus. Besides this, the role of deformations and angular momentum is also investigated in the decay of odd nuclear system $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$. The mass fragmentation process changes from symmetric to asymmetric with inclusion of β_2 -deformation in $^{213}\text{Fr}^*$ and $^{217}\text{Fr}^*$. The mass fragmentation seems to depend largely on angular momentum, the light particles being more prominent at lower ℓ -values and higher fragments start competing with lighter ones at higher values of ℓ .

In the last chapter, we have investigated the role of deformation and orientation of the decaying parent nucleus and of emitted fragment(s) in the ground-state decay of the daughter nucleus, using the preformed cluster model (PCM) of Gupta and collaborators. The interesting point is that both the preformation factor P_0 and penetrability P are shown to get modified with the inclusion of deformation and orientation effects. Moreover, unlike P , the P_0 is affected not only due to the shapes of parent, daughter and cluster nuclei, but also due to the shapes of all other possible fragmentation of the decaying parent nucleus. We have studied the role of deformation and orientation for all measured clusters including the very recent experiments of ^{14}C and ^{15}N decays from ^{223}Ac and ^{34}Si emitted from ^{238}U . We consider here the cluster radioactive decays where both the daughter and cluster are spherical and or deformed and orientated. We find that β_2 alone is good enough to fit the experimental data, whereas the inclusion of higher multi-pole deformations either show an anomalous behavior or the observed cluster is not an obvious choice because it is either not energetically favored (not at the minimum in the calculated

fragmentation potential) or excluded by the penetrability factor. However, higher multi-pole deformation effects seem essential for ^{14}C decay. In conclusion, the role of deformations and orientations is extremely desirable as that of shell effects and Q-values.

It may be noticed that in the present work we have confined ourselves to quadrupole deformations (except for ^{14}C cluster decay) using optimum orientations criteria. However there is definite scope of extension of this work by exploring the role of higher multipole deformations within generalized orientation approach, both coplanar and non-coplanar orientations in compact configurations.

