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CHAPTER 1

Introduction

From the earliest days of human existence, mankind has been innately driven by the profound curiosity to understand the cosmos. As intellectual thought evolved over centuries, philosophical interpretations of natural phenomena gradually gave way to systematic scientific frameworks rooted in the empirical observations and mathematical formalisms. The quest for understanding was not confined to the vast expanse of the celestial sphere, it extended deep into the microscopic realm, laying the foundation of the modern atomic and subatomic physics. One of the most transformative milestones in this journey was the discovery of radioactivity in 1896 by Henri Becquerel [?]. Studies led by Marie and Pierre Curie established the phenomenon of spontaneous nuclear transformations. Which describes the dynamic and intricate nature of the atomic nucleus. Their research further culminated in the discovery of new radioactive elements such as Polonium and Radium, whose remarkable properties demonstrated not only the immense energy stored within the nucleus, but also its ability to enable a wide range of physical, industrial and medical applications including the early development of radiation therapy. The investigation of these elements revolutionized our knowledge of atomic structure and established the foundation of modern nuclear science by providing evidence that the atoms are dynamic systems capable of transformation rather than indivisible or immutable as previously believed.

Its implications extended to cosmology, offering indirect support for the Big Bang theory. The Big Bang refers to the moment when all the energy and matter of the universe, confined within an infinitely dense and extremely hot singularity, which underwent rapid expansion. This event created a seething “soup” of fundamental particles such as quarks

and leptons. As the universe cooled, these particles combined to form protons and electrons. According to stellar nucleosynthesis models, the universe was hot and dense enough to sustain nuclear fusion reactions similar to those in stars, leading to the formation of light elements. As the universe cooled during the era of recombination, fundamental forces such as electromagnetic, weak, and strong interactions emerged distinctly. These forces govern the behavior of atomic and subatomic particles and shaped the evolution of the universe. Even at the age of billion years these interactions lead to the expansion of the universe and possess numerous galaxies as the coalition of light elements leads to the formation of hydrogen and helium gases.

Modern nuclear physics began with the shift from cosmic to subatomic exploration. Which was propelled by a series of landmark experiments during the late 19th and early 20th centuries that fundamentally shaped our understanding of the atomic nucleus. The discovery of the electron by J. J. Thomson revealed the existence of subatomic constituents, while Ernest Rutherford's gold foil experiment established the nucleus as the dense, positively charged core of the atom. Subsequently, Frederick Soddy and Rutherford presented the concept of radioactive decay chains and nuclear transmutation, which demonstrated that atoms of certain elements could spontaneously transform into other elements by emitting radiation. This transformation involved a measurable loss of mass, which, when interpreted through Einstein's mass-energy equivalence relation $E=mc^2$, made clear that even a small decrease in mass could produce a substantial release of energy. Together, these contributions provided the first empirical and theoretical basis for linking nuclear transformations with energy production. This framework was completed in 1932 by James Chadwick's discovery of the neutron [?], which clarified the isotopic composition and the additional source of nuclear binding.

Together, these discoveries laid the foundation for modern nuclear models and experimental nuclear physics, paving the way for a deeper investigation of nuclear stability, radioactivity and nuclear reactions. One of the first and most significant breakthroughs came in 1928, when George Gamow [?] introduced the quantum mechanical explanation of α decay, showing that the emission of a helium nucleus (^4He) could be explained through

the process of quantum tunneling, in which the decay constant is directly correlated with the barrier penetration probability. This marked the first successful application of quantum mechanics to nuclear decay phenomena and established a framework that is still essential for comprehending the radioactive processes. A decade later, the experimental work of Otto Hahn and Fritz Strassmann [?] provided the first evidence that a heavy nucleus such as uranium could split into two lighter nuclei, leading to the phenomenon of nuclear fission. The phenomenon of spontaneous and induced fission in heavy nuclei was soon established as an additional decay mode, complementing α , β and γ -emissions.

Subsequent theoretical models such as the liquid drop model [?], the nuclear shell model [?] and the collective model enriched the understanding of the nuclear structure and nuclear reactions. Together, these theoretical advances provided a comprehensive foundation for describing nuclear stability, formalism and decay mechanisms of nuclear reactions, while opening avenues for the study of more complex processes. A systematic representation of isotopes in terms of their proton and neutron number is illustrated through chart of nuclides, also known as the valley of stability is shown in Fig. 1.1. It summarizes the systematic trends of nuclear stability and the decay modes. Stable and long-lived nuclei are located along the line of stability, while isotopes away from this region undergo characteristic decays such as beta decay, alpha decay and spontaneous fission. Enhanced stability at shell closures is also evident, reflecting the role of nuclear shell effects. In addition to conventional decay modes, nuclei with large mass and charge may also undergo ternary or quaternary fission. Which leads to the emission of three or four fragments from the radioactive nuclei.

This leads to crucial observation that heavy nuclei exhibit competition between different fragmentation pathways. Such decay processes may be governed by shell effects, deformations, collective dynamics, orientations and geometry. The prime aim of this study is to explore the dynamic evolution of various radioactive decay modes. A brief description of related processes and mechanisms is given below.

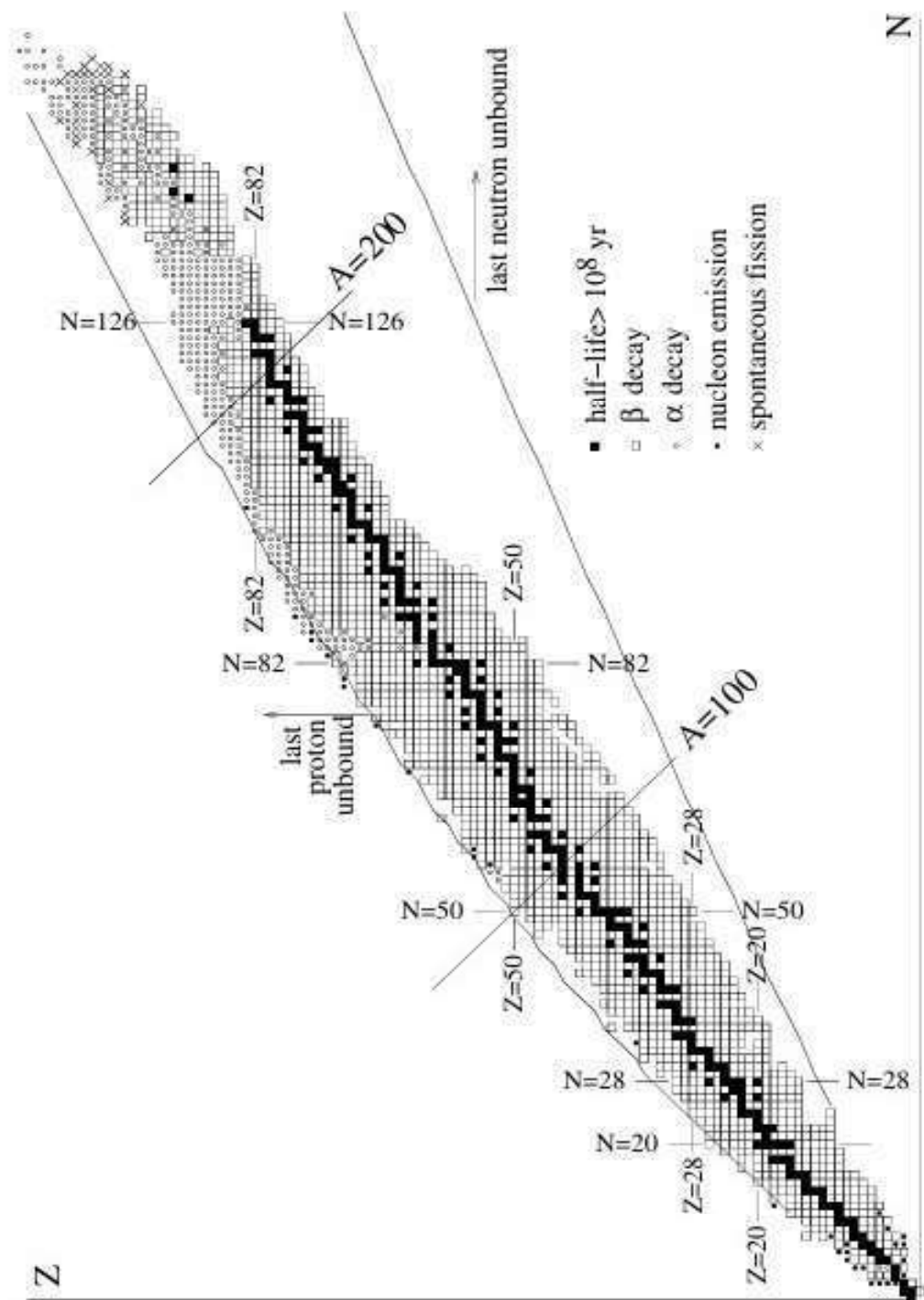


Figure 1.1: The island of stability illustrating the various radioactive decay modes i.e., alpha decay, beta decay, spontaneous fission, etc.

1.1 Radioactive Decay

Radioactive decay represents a mechanism of unstable nuclei which attains stability through the emission of mass and energy. Heavy nuclei can decay via multiple decay channels, i.e. (a) binary fission [?] (b) ternary fission [?] and (c) quaternary fission [?]. Binary fission remains the most dominant and imparts useful insights in reference to nuclear structure and stability, despite having numerous applications particularly in the defence and energy sector. The rarer fission phenomenon such as ternary or quaternary emissions are also being investigated to reveal deeper understanding of related processes. It will be of interest to do a comprehensive analysis of these decay modes. In view of this, the aim is to study binary, ternary and quaternary decay mechanisms. A brief discussion of these decay modes is described as follows:

1.2 Binary Decay

The disintegration of the unstable nucleus into two distinct fragments is called binary decay. The nuclei belonging to the heavy mass region are mostly radioactive. Experimental [?] and theoretical observations [?] concluded that such radioactive nuclei may undergo alpha emission, cluster radioactivity (CR), heavy particle radioactivity (HPR) and spontaneous fission (SF) as shown in Fig. 1.2. Among these, alpha decay is the most common process, characterized by emission of an alpha particle from the unstable nucleus [?]. Spontaneous fission, on the other hand, involves the division of a heavy nucleus into two fragments of nearly comparable masses and represents another dominant decay channel in heavy nuclei. In 1939, fission was discovered [?], where the emitted fragments of comparable size were observed. After the establishment of alpha and spontaneous fission processes, the cluster decay mode, also known as cluster radioactivity (CR), came into the picture. Theoretically predicted by Greiner *et al* [?] and experimentally observed by Rose and Jones [?], CR, the emitted fragment is heavier than an alpha particle but much lighter than the fission fragments. Till now, clusters such as ^{14}C , $^{18,20}\text{O}$, ^{23}F , $^{24,26}\text{Ne}$, $^{28,30}\text{Mg}$, ^{34}Si have been experimentally observed in the decay of the heavy-mass region [?]. Further, another kind of radioactivity was predicted

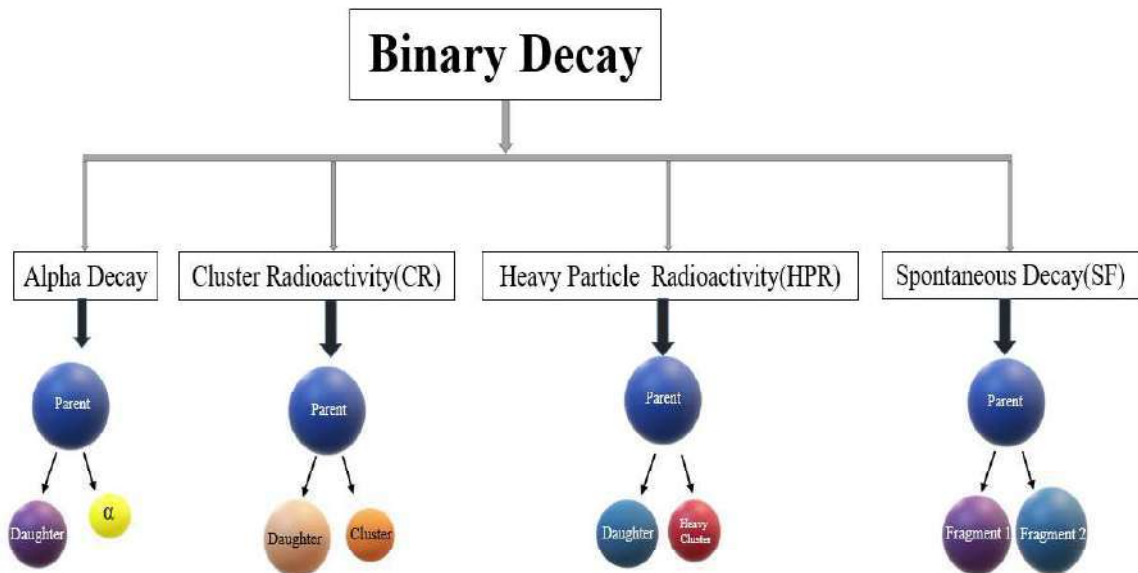


Figure 1.2: A schematic representation of various ground state decay mechanisms evolved via binary path.

in which the emitted fragment is heavier than cluster but lighter than fission fragment is observed, and the process is called heavy particle radioactivity (HPR) [? ?]. Hence, binary fission includes different decay modes (α , CR, HPR, SF), and it will be of interest to explore various properties associated with them. The occurrence of these processes is strongly governed by the underlying nuclear shell effects, which play a decisive role in reference to stability, structure and mass distribution of decay fragments. Nuclei with closed shells (proton or neutron) are preferentially produced as decay fragments due to their enhanced binding energy [?]. Furthermore, deformations [? ?] also play a decisive role in the fragment identification. Given the crucial role of deformations and shell effects in determining decay pathways, it is essential to explore their impact in reference to underlined effects. Accordingly, the present thesis includes a comprehensive investigation of binary decay processes, as elaborated in Chapter 3. Furthermore, it is important to note here that the radioactive nuclei can also decay via ternary channel, in which three fragments are emitted in the decay event. This rare and complex phenomenon is examined in the subsequent section.

1.3 Ternary Decay

The radioactive emission in which three fragments are emitted rather than the usual two fragments is termed as ternary fission (TF). Firstly, observed by Alvarez *et al.* [1], where a long-range alpha particle was detected along with two fission fragments. Subsequent studies by Muga *et al.* [2] show the nuclear emulsion technique to photograph the three fragments emitted in spontaneous ternary fission. Interestingly, an alpha particle is registered along with two heavy fragments in the ternary fission of the heavy nuclei [3, 4]. These foundational experiments spurred further investigations, revealing that, in addition to long-range alpha particles, heavier light charged particles such as ^{10}Be , ^{14}C could occasionally accompany fission fragments [5, 6, 7, 8, 9]. The other light nuclei, such as $^{1,2,3}\text{H}$, $^{6,8}\text{He}$, $^{6,7,8,9}\text{Li}$ and $^{9,10}\text{Be}$, have also been observed in the spontaneous ternary fission [10, 11, 12]. Therefore, if a radioactive nucleus undergoes fission, accompanied by the emission of a light charged particle along with two fission fragments, the process is referred to as particle-accompanied fission.

Recent experiments conducted by Yu.V.Pyatkov *et al.* [13] show heavy clusters like ^{52}Ca , along with two heavy fragments. This mode of decay where three fragments of comparable size are emitted is referred as true ternary fission (TTF). Studies [14, 15] have indicated that the clustering of three bodies can occur via two geometries involving prolate (collinear) and oblate (equatorial) shapes as shown in Fig. 1.3. Diehl and Greiner [16] have shown the preference for prolate over oblate shape for ternary decay. In equatorial emission (Fig. 1.3(a)), the third fragment is emitted nearly perpendicular to the fission axis from the neck of two heavier fragments, while in collinear emission (Fig. 1.3(b)), the third fragment is emitted collinearly, along the same axis as the fission fragments [17, 18]. However, the probability of ternary fission is approximately 4×10^{-3} per spontaneous fission (SF) event [19]. Theoretical studies [20, 21] within the framework of the modified liquid drop model and macroscopic potential energy surface (PES) landscapes have been used to identify the heights and locations of binary and ternary saddle points [22, 23]. These studies conclude that the probability of ternary fission increases with the atomic number of the fissioning system. To understand the ternary fission of various heavy nuclei, extensive

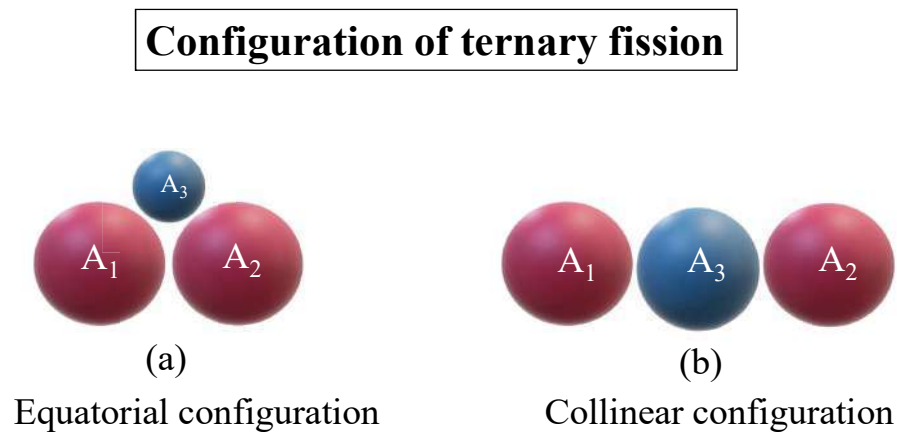


Figure 1.3: Schematic representation of different configurations of three fragments (a) equatorial and (b) collinear configuration.

efforts have been made to investigate the relative contributions of heavier and lighter third fragment [? ? ? ? ? ? ? ?]. These investigations underscore the predominance of light charged particles, particularly alpha particles, in ternary fission, alongside the significant role of heavier fragments, offering critical insights into nuclear dynamics and fragment distributions. An explanation of light-charged particle-accompanied fission (LCP) and true ternary fission (TTF) is given below.

1.3.1 Light Charged Particle (LCP) Accompanied Fission

During ternary fission (TF), the most commonly observed process is the emission of a LCP with two fission fragments. Various authors [? ? ? ? ? ? ? ?] have observed a variety of light-charged ternary particles such as ${}^{3,2,1}\text{H}$, ${}^{8,6,5,4,3}\text{He}$, ${}^8\text{Li}$, ${}^{10}\text{Be}$, and ${}^{14}\text{C}$. In the heavy-mass region, ternary fission accompanied by LCP emission has been extensively documented for several actinide nuclei, notably for ${}^{244}\text{Cm}$ [?], ${}^{238}\text{Pu}$, ${}^{240}\text{Pu}$, ${}^{242}\text{Pu}$, and ${}^{244}\text{Pu}$ [?] and ${}^{252}\text{Cf}$ [?]. These studies consistently demonstrate that among all possible LCPs, the yield of α -accompanied ternary fission is significantly higher than that of other light clusters. Experimental studies [? ?] have also reported the occurrence of both binary and ternary cold spontaneous fission modes in the case of ${}^{252}\text{Cf}$. An investigation [?] of the bimodal fission behavior of ${}^{252}\text{Cf}$ revealed binary fragmentation channels such as

Ru-Xe and Mo-Ba, along with ternary splits including Zr- α -Ba, Xe- α -Mo, and Ru- α -Te. From a theoretical point of view, the ternary fission process has been systematically investigated, where various models such as the three-cluster approach [1, 2, 3, 4, 5], potential energy surface calculations [6], and micro-macroscopic formalisms [7] have been employed to determine the favored fragmentation channels and the corresponding barrier characteristics. In the present thesis, three cluster model (TCM) is employed to study ternary decay. A detailed analysis of ternary emission from ^{252}Cf nucleus is detailed in chapter 4. Additionally, there exists the possibility of true ternary fission (TTF), a decay mode in which all three emitted fragments are of comparable size. This process is discussed below.

1.3.2 True ternary fission (TTF)

While most experimental studies have focused primarily on LCP emission, there also exists the possibility of a decay mode in which a comparatively heavier fragment is emitted alongside the two main fission fragments. This process is referred to as true ternary fission (TTF). TTF seems to prefer the collinear geometry, where three fragments are emitted along the fission axis shown in Fig. 1.3(b). Recently, Pyatkov *et al.* [8] observed true ternary fission for spontaneous fission of ^{252}Cf and neutron-induced fission of $^{235}\text{U}(\text{n},\text{fff})$ nucleus using the missing mass method with two FOBOS detectors in coincidence at 180° . In these experiments, $^{48-56}\text{Ca}$ are reported as a third fragment along with $^{68-74}\text{Ni}$ and $^{129-133}\text{Sn}$ for spontaneous ternary fission of ^{252}Cf nucleus. Theoretically, the true ternary fission of ^{252}Cf has been studied [9] and three possible fragments are predicted on the basis of potential energy surfaces. As a result, three fragments with proton magic numbers $Z = 50, 28$, and 20 were identified, each possessing comparable masses. It may be noted that the shell effects and deformations [10, 11] play a crucial role in the identification of most probable fragments and their respective yields [12]. Recently, excitation-energy-dependent potential energy surfaces for tripartition of ^{252}Cf were studied by taking orientation angles as 0° - 0° [13]. In view of this, the relevance of deformations and orientations is investigated in reference to binary and ternary fission, for spontaneous as well as induced processes.

1.4 Quaternary Fission

Quaternary fission is a rare decay mode that involves the emission of four fragments from the radioactive parent nucleus. Experimental studies [?] demonstrate the presence of quaternary fission in $^{235}\text{U}(n,f)$ induced by thermal neutrons and in spontaneous fission of ^{252}Cf . Quaternary fission yields are significantly higher in spontaneous fission of ^{252}Cf , emitting particles such as (α,α) , (α,t) , and (t,t) with two heavy fragments, where α and t refer to α -particle and tritium. In quaternary fission, if two lighter fragments are emitted alongside two heavier fragments, it is referred as light charged particle (LCP) emission [?]. Evidence [?] provides that (α,p) is also detected in the quaternary fission of the ^{252}Cf nucleus. Such processes are indicative of complex fission dynamics wherein unstable nuclei facilitate the emission of light-charged particles (LCPs) [? ? ? ? ?]. Recent experimental work conducted by Pytakov *et al.* [?] has explored multibody decay, shedding light on the true quaternary decay (true is used to underline that all decay products have comparable size. There are two classifications for quaternary fission: One is spontaneous quaternary decay, where four decaying fragments emerge simultaneously. However, the second is pseudoquaternary fission. This process takes place in two stages hence the a sequential process. The first stage is the emission of three fragments with one unstable fragment. Which further decays into two lighter fragments, leads to the second stage of the fission mechanism. Numerous studies [?] have been conducted to gain a deeper understanding of the mechanisms underlying the multicluster emission. These studies shows that various configurations are energetically preferred for multicluster decay [?]. Each configuration is associated with potential energy values, as the different fragment arrangements lead to differences in the interactions involved. The lower magnitude corresponds to a more stable emission mode. To understand the complex phenomena, many theoretical models were introduced. These models highlight the significant role of shell effects in decay, particularly emphasizing the strong shell effects associated with the doubly magic heavy fragment ^{132}Sn [?]. The relevance and influence of such shell effects across potential energy are crucial in understanding the dynamics of the nuclear fragmentation process.

1.5 Heavy ion-induced reactions at low energy regime

In addition to spontaneous fission, nuclear breakup can also occur as a result of nuclear reactions induced by the interaction between projectile (P) and target (T) nuclei. The study of nuclear reactions has long been employed as a powerful tool to explore the underlying nature of nuclear forces across a broad range of P–T combinations. In particular, low-energy heavy-ion collisions offer a valuable framework for probing the ion–ion interaction potential. Such investigations are essential for gaining deeper insight into nuclear stability, reaction dynamics, and the underlying mechanisms governing various decay processes.

The possible combinations of projectile and target nuclei may result in the formation of a compound nucleus (CN) in an excited state. Such a CN is unstable and subsequently de-excites by breaking into two fragments under various conditions influenced by parameters such as angular momentum, temperature, nuclear deformations, and orientations [?]. The decay of a compound nucleus primarily occurs through two major channels: (i) the first involves the emission of multiple light particles (LPs), commonly referred to as evaporation residues (ER), which include neutrons (n), protons (p), α -particles, γ -rays, and (ii) the second dominant mode is in which compound nucleus splits into two fragments of comparable mass ($A/2 \pm 20$). In some cases, additional contributions arise from *intermediate mass fragments (IMFs)*, often identified as clusters, with mass numbers in the range $5 \leq A \leq 20$ and charge numbers $2 \leq Z \leq 10$. In addition, *heavy mass fragments (HMFs)*, which occupy the intermediate region between IMFs and fission fragments, may also appear [?]. The IMF and HMF emission is significant only in selected nuclear systems, the dominant decay contributions at low excitation energies typically stem from light-particle evaporation and fission processes.

In addition to compound nuclear processes, non-compound nucleus (nCN) reactions also play important role in understanding reaction dynamics and nuclear structure. Unlike CN formation, nCN processes involve interactions of the projectile with a small number of nucleons (typically two to five) within the target. To investigate heavy-ion-induced reactions (CN and nCN) numerous theoretical models [? ?] and frameworks have been developed. These theoretical approaches emphasize that the total interaction potential

serves as a fundamental quantity to obtain a comprehensive understanding of the reaction dynamics and associated nuclear properties. In the present work, induced fission is discussed in Chapter 6.

Additionally, to understand the dynamics of nuclear interactions, it is important to select an appropriate nuclear interaction potential. In the following section, a brief account of the nucleus–nucleus interaction potentials used in this work is outlined.

1.6 Nucleus-Nucleus Interaction

In recent years, numerous theoretical models have been developed to explain various aspects related to formation and decay dynamics. As two nuclei come into proximity, their interaction is governed by the interplay of a long-range repulsive Coulomb force and a short-range attractive nuclear potential. These potentials interplay to form an interaction barrier. Within this barrier, the short-range component of the interaction plays a dominant role in shaping the overall potential profile [1–3]. To describe the nuclear interactions the two most widely adopted approaches are phenomenological [4–6] and microscopic methods [7–10]. Collectively, these studies emphasize the need for accurate modeling of nuclear potential in order to understand the complex interplay of forces during the fragmentation process. A brief discussion of these methods is given below.

1.6.1 Proximity Potential

The proximity potential approximates the nuclear potential on the basis of the proximity of the surfaces of interacting nuclei. It is widely accepted as a fundamental framework for interpreting the decay dynamics associated with the fusion–fission process. Firstly it was used by Bass [11]. Then efforts were made by Blocki *et al.* [12], to introduce a formula to calculate nuclear potential as a function of separation distance of two interacting nuclei. It simplifies the calculations involving nuclear interactions and uses empirical data to parameterize it. All proximity potentials [13–17] originate from the concept of proximity forces, which is based on a theorem stating that when two gently curved surfaces are brought sufficiently close, the resulting force between them can be approximated by the interaction energy per unit area of two parallel flat surfaces composed

of the same material. The proximity potential is the product of a geometrical factor and a universal function that encapsulates the dependence on the separation between interacting surfaces. In addition to these proximity models, several other nuclear potentials, such as those derived through the double-folding procedure using phenomenological forms such as the Yukawa plus exponential potentials [?]. These models have been successfully employed to reproduce experimental mass distributions and half-lives, demonstrating their reliability and physical consistency. These theoretical frameworks and their corresponding formulations are discussed in detail in Chapter 2 of the thesis.

1.6.2 Skyrme-based Approach

In contrast to phenomenological models, the microscopic Skyrme-based approach derives the nucleus–nucleus potential from the Skyrme Energy Density Formalism (SEDF). This framework offers a fundamental microscopic interpretation of nuclear interactions and has been mostly used to describe the complex dynamics governing nuclear fusion, fission and various radioactive decay processes. SEDF approach is based on the Energy Density Formalism (EDF), which is one of the most powerful theoretical tool for interpreting nuclear reactions and nuclear structure. This concept was first proposed by Hohenberg and Kohn [?] and later extended by Kohn and Sham [?], which states that the total energy of a system of interacting fermions in its ground state can be expressed as a function of the local density and its gradients. Although this concept is originally formulated for electronic systems, was subsequently generalized for nuclear systems, where the nucleon density plays a role analogous to the electronic charge density.

The EDF approach simplifies the many-body nuclear problem by reducing it to a local functional representation, thereby avoiding the explicit use of complex many-body wave-functions. Building on this foundation, Vautherin and Brink applied the Hartree–Fock (HF) method to study effective nucleon-nucleon interactions to derive the nuclear binding energy and potential for spherical nuclei [?]. In their formulation, the total energy density is expressed in terms of three fundamental quantities: kinetic energy density (τ), nucleon mass density (ρ) and spin–orbit density (J). HF calculations could not be implemented within the energy density formalism because the kinetic-energy-density τ was not available.

To overcome this limitation, semiclassical methods such as the Thomas–Fermi (TF) and Extended Thomas–Fermi (ETF) approximations were introduced. These methods express kinetic and spin–orbit energy densities as functions of nucleon density, thereby reducing computational complexity while retaining the essential physics. The ETF approximation, developed by Grammaticos and Voros [?], allows the total energy to be treated as a function of nucleon density alone, facilitating the study of reaction dynamics. In this framework, the hamiltonian employed did not include any spin-dependent contributions. However, it is well established that an accurate representation of nuclear structure requires the incorporation of a spin–orbit interaction, particularly after its decisive role was recognized through the success of the Shell Model. To address this limitation, Ref. [81] extended the formalism by incorporating the spin–orbit component into the semi-classical expansion, thereby adapting the method to a more realistic scenario where spin–orbit and density-dependent terms are explicitly included in the effective one-body Hamiltonian. Within the semi-classical framework, the spin–orbit density J_q becomes an explicit function of the nucleon density. Consequently, J_q assumes non-zero values even for nuclei possessing completely filled shells. This behavior stands in contrast to the microscopic shell-model description, in which the spin–orbit density vanishes for such closed-shell configurations due to exact cancellations between spin–orbit partner states.

Within the SEDF framework, the interaction potential is generally evaluated under two limiting density approximations: the adiabatic and the sudden (or frozen) approximations. In the adiabatic case, the nucleon distributions of the interacting nuclei gradually adjust to achieve local equilibrium, which is suitable for slow reactions. Conversely, in the sudden approximation, the densities of the projectile and target overlap without significant rearrangement, corresponding to fast processes such as low-energy heavy-ion collisions. In the frozen density approximation, a variant of the sudden model the total density of the interacting system is approximated as the sum of the individual densities of the colliding partners. Studies have shown that this approach yields realistic potential energy surfaces consistent with experimental data. Therefore, in the present work, frozen density is used to understand the fission dynamics.

1.7 Motivation

The actinide region is studied as it occupies a unique position in the nuclear chart. The nuclei belonging to this region are unstable, which enable the possibility of exploring multiple decay channels. The focus on binary fission alone is no longer suffices, as experimental observations increasingly indicate the co-existence of multiple pathways (ternary and quaternary fission) within the same nucleus. This demands a systematic and comparative theoretical framework to explore the mechanism of various channels operating in the nuclear decay dynamics.

In the present work, actinide nuclei are chosen as the inherent radioactivity enables a variety of decay processes such as binary, ternary and quaternary fission. The first objective of this thesis concentrates on the binary decay channels such α -decay, CR, HPR, SF. To accomplish this, the preformed cluster model (PCM) is employed as theoretical framework. Within this model, decay properties are analyzed in terms of preformation probability, barrier penetration probability, and half-life. The inclusion of both spherical and deformed fragment configurations allows for a more realistic description of the mass distribution and enhances the predictive power of the model.

Beyond conventional two body decay fragmentation, experimental studies reported involving three or more fragments in the decay process. This reveals that heavy nuclei can undergo decay modes such as ternary and quaternary fission. To achieve a holistic view, it is essential to investigate these multicluster decay modes alongside binary fission. The present study extends the theoretical framework through three cluster Model (TCM) and further generalises for quaternary fission. Since ground-state deformations exert a significant influence on the fission dynamics, they play a decisive role in determining the most probable decay channels. Consequently, the identification of the most favorable fragment combinations in both binary and ternary fission necessitates the explicit consideration of deformation effects.

The present thesis seeks to establish a comparative analysis of binary, ternary and quaternary fission modes in the actinide region. This not only bridges gap between theoretical descriptions but also provide predictive insights into complex decay modes, guiding future

experimental investigations. To ensure a systematic and comprehensive treatment of these multicluster emission phenomena, the present thesis is organized around the following key objectives:

1. Decay prospects of actinides and heavier nuclei via particle emission, α decay, cluster radioactivity, heavy particle radioactivity and spontaneous fission.
2. Analysis of multicluster emission such as binary, ternary and quaternary fission.
3. Impact of proximity and Skyrme-based nuclear potentials in fragmentation analysis.
4. The results will be compared with available experimental data and an attempt will be made to explore relevant predictions for future validations.

The organization of the thesis, based on the aforementioned objectives, is outlined in the following section.

1.8 Organisation of the Thesis

The organization detail of the present thesis is given below:

In **Chapter 2** of the thesis, the fundamental formalism of the quantum mechanical fragmentation theory (QMFT) are presented. Within this framework, the preformed cluster model (PCM) and the three-cluster model (TCM) are formulated. The formalism is further extended to quaternary fission, wherein the parent nucleus undergoes simultaneous emission of four fragments. In PCM framework, particular emphasis is placed on the evaluation of the preformation probability and the three-step barrier penetration probability, which together provide a quantitative description of the decay mechanism. Furthermore, the construction of potential energy surfaces, mass distributions and relative yield are discussed in detail to establish a comprehensive theoretical basis for the subsequent fission processes. In addition to PCM and TCM, DCM has been employed to investigate the dynamics of heavy-ion induced reactions.

In **Chapter 3**, binary (α , CF, HPR, and SF) decay analysis for the nuclei ranging $Z=89-102$ is carried out. The dynamical evolution of alpha decay, cluster radioactivity (CR), heavy particle radioactivity (HPR), and spontaneous fission (SF) processes is worked

out. Firstly, the α -decay $\log T_{1/2}$ are calculated for two sets of chosen nuclei by fitting ΔR . The obtained ΔR is further used to calculate Q-value dependent first turning point i.e. $R_a(Q)$. The $R_a(Q)$ relations are employed to calculate α decay half-lives of other set of nuclei with in chosen range and found to be in good agreement with the experimental data. After the alpha decay analysis, the $R_a(Q)$ relations are obtained for CR and HPR decay modes. In the case of CR, the $R_a(Q)$ relation with deformed choice gives better agreement as compared to the spherical choice. Further, SF is studied using fragmentation potential and preformation distribution for extreme choice of nuclei (^{230}Th and ^{256}No) in range $Z=89-102$. The mass distribution of the ^{230}Th and ^{256}No nuclei are studied, and it is observed that the it changes from asymmetric to symmetric. In order to study the transition point, mass distribution of ^{252}Cf and ^{256}fm along with extreme nuclei in range $Z=89-102$ (^{230}Th and ^{256}No) is studied. In addition to this, the TKE of these fission fragments is calculated and compared with experimental data.

Chapter 4, extends to investigate binary and ternary fission modes of the ^{252}Cf , incorporating deformation and orientation effects. The β_2 deformed hot-compact/ $90^0-90^0/0^0-90^0/90^0-0^0$ and cold-elongated/ 0^0-0^0 orientations are incorporated in the present analysis. For the compact configurations, the decay pattern exhibits a clear predominance of symmetric and near-symmetric fragmentation channels, which is primarily governed by the stabilizing influence of spherical magic shell closures. In contrast, the elongated orientations reveal a distinctly asymmetric yield distribution, wherein the dominance of deformed magic shell closures becomes evident, leading to enhanced probabilities for mass-asymmetric decay modes. Further, the study examines the influence of equatorial cluster tripartition (ECT) and collinear cluster tripartition (CCT) configurations in ternary decay. The corresponding fragmentation potential and relative yield is computed and compared with experimental observations. This provides a deeper insight into the role of deformation in fission dynamics.

In **Chapter 5**, a comprehensive investigation of binary, ternary, and quaternary fission of the ^{252}Cf nucleus is carried out in terms of fragmentation potentials and barrier characteristics. Various decay channels (^4He , ^{46}Ar , ^{82}Ge and ^{116}Pd) associated with binary fission are systematically explored. Subsequently the investigations extends to the feasibility of

ternary fission of the same nucleus by keeping ^4He , ^{46}Ar and ^{82}Ge as fixed third fragment. Therefore, the identification of most probable fragment are attributed to the presence of shell closure. Further, quaternary fission is studied with particular emphasis on scenarios involving two fixed fragments, while investigating different possible collinear configurations. A comparison of all probable geometrical configurations in quaternary fission is made and arrangement with elongated neck between two heavy fragments is found as most probable mode. In addition to the geometrical arrangement, all energetically favourable fragment combinations are identified, providing valuable insights into the competing decay modes of ^{252}Cf .

In **Chapter 6**, in this chapter, ground state spontaneous binary and ternary fission of ^{252}Cf is studied. Firstly, the binary fragmentation potential of ^{252}Cf is calculated by employing the two types of nuclear potentials. One with the proximity and the other with SEDF-based potential. The different potentials significantly modify the structure and magnitude of the fragmentation potential. Notably, calculations using the SEDF approach (SKT3 force) demonstrate a reasonable agreement with experimental half-lives, validating the choice of nuclear potential. Furthermore, the SKT3 force is employed to investigate the ternary fission process in the decay of the ^{252}Cf nucleus. The three-body fragmentation potential is calculated by considering spherical and deformed choices of decaying fragments. The relative yield for the ternary fission of the ^{252}Cf nucleus is calculated for the deformed case and compared with experimental data.

In addition to this ground state decay process, the decay dynamics of compound nuclear system, i.e. $^{228}\text{U}^*$, formed via $^{31}\text{Al} + ^{197}\text{Au}$ reaction within the framework of DCM is analysed. The most probable fission fragments of $^{228}\text{U}^*$ CN appearing in the asymmetric region have neutron magic configuration, and hence result in higher binding energy/stability. Similarly analysis has also been observed for another choice of projectile-target combination (i.e. $^{19}\text{F} + ^{209}\text{Bi}$), forming the same CN ($^{228}\text{U}^*$). Important to mention, the above result is independent of the choice of Skyrme forces, i.e. SIII and SSk, although they modify the barrier significantly.

At the end, **Chapter 7** gives a brief note on the work done in reference to the objectives of the present thesis along with the future possibilities that arise from the established

results.

CHAPTER 2

Methodology

2.1 Introduction

In the previous chapter, the evolution of nuclear decay processes and methods was presented, with particular emphasis on ground-state decay modes and heavy-ion-induced reactions. Their physical significance and relevance in understanding nuclear stability and reaction dynamics were highlighted. These discussions lay the conceptual foundation for the present chapter, which focuses on the theoretical methodology used in context of nuclear dynamics. Over the past several decades, extensive experimental [? ? ?] and theoretical [? ? ? ?] study of nuclear decay is done to understand the underlying mechanisms governing nuclear stability. Experimentally, numerous measurements have been performed to identify and characterize various decay modes, ranging from well-established processes such as α -decay and SF to more exotic modes such as cluster radioactivity and multicluster emissions (ternary and quaternary decay modes). Parallel to these developments, a variety of theoretical formulations have been introduced to explain the underlying mechanisms and impart predictions for future exploration in the related area.

The present chapter provides a detailed account of the theoretical framework adopted for analyzing the decay of radioactive nuclei. Binary decay characteristics are investigated within the framework of the Preformed Cluster Model (PCM) [? ?], while the Three-Cluster Model (TCM) [? ? ?] is utilized to examine the ternary decay mechanisms. In addition, the model is extended to study quaternary fission, where four fragments are simultaneously emitted from a parent nucleus. These models, which are primarily

focused on ground-state decay phenomena, assume the absence of temperature and angular momentum effects, thereby providing an effective description of spontaneous or cold decay processes.

To extend the theoretical understanding towards the excited nuclear system formed in heavy-ion induced reaction, where both temperature (T) and angular momentum play significant roles, the Dynamical cluster decay model (DCM) is adopted as a modified version of the PCM. These formulations are fundamentally derived from the principles of Quantum Mechanical Fragmentation Theory (QMFT) [? ? ? ?], which serves as the underlying theoretical basis for describing nuclear fragmentation phenomena in a unified manner.

2.2 Quantum Mechanical Fragmentation Theory

QMFT is a description to understand decay dynamics, employing charge (η_z) and mass (η_A) asymmetry coordinates represented as $\eta_z = \frac{(Z_1 - Z_2)}{(Z_1 + Z_2)}$ and $\eta_A = \frac{(A_1 - A_2)}{(A_1 + A_2)}$. In the present framework, it is postulated that the parent nucleus contain all possible decay fragments prior to their actual separation. The probability of the preformation of decaying fragments is termed as preformation probability (P_o). P_o is obtained by solving the time independent Schrödinger equation in the mass (or charge) asymmetry coordinate. Once preformed, the fragments may penetrate through the barrier potential, defined by the total potential energy surface, by overcoming the first turning point of the potential pocket.

In addition to the η_z and η_A coordinates, several other collective coordinates are employed to describe the comprehensive dynamics of the radioactive and synthesized nuclear systems. These include the inter-nuclear separation distance R , multipole deformation parameters ($\beta_{\lambda i}$) of the fragments, the azimuthal orientation angle ϕ between their principal planes, and the neck parameter ϵ between the two interacting nuclei. Collectively, these variables define the potential energy landscape governing the fragmentation process.

A description of PCM, TCM, and DCM models is presented in the following sections, where their respective formulations are employed to investigate binary, ternary, and heavy-ion-induced decay mechanisms. Here PCM, TCM and DCM refer to preformed cluster model, three cluster model and dynamical decay cluster model.

2.3 Preformed Cluster Model [PCM]

PCM [?] is formulated on the assumption that the decaying fragments are preformed as separate entities inside the parent nucleus before the actual decay process takes place. Within this theoretical formalism, the decay dynamics are governed by η_A coordinate and the relative separation coordinate R . As discussed above, the stationary Schrödinger equation describing the collective dynamics of a fragmenting nucleus in terms of mass asymmetry coordinate η and relative separation coordinate R can be expressed as:

$$\left\{ -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V_R(\eta, T) \right\} \psi^\nu(\eta) = E^\nu \psi^\nu(\eta), \quad (2.1)$$

Here, $\nu = 0$ corresponds to the ground-state solution, and ($\nu = 1, 2, 3, \dots$) represents the excited states. The ground state preformation probability P_0 is defined as

$$P_0 = \sqrt{B_{\eta\eta}} |\psi(\eta(A_i))|^2 \frac{2}{A_{CN}}, \quad (2.2)$$

In order to solve eqn. 2.1, the two body fragmentation potential may be expressed as follows: [?]:

$$V_R(\eta, R) = \sum_{i=1}^2 B(A_i, Z_i) + V_P(A_i, R, \beta_{\lambda i}, \phi, \theta_i) + V_C(Z_i, R, \beta_{\lambda i}, \phi, \theta_i) \quad (2.3)$$

Here, $B(A_i, Z_i)$ (taken from [?]) represents the binding energy of fragment i . While V_P and V_C are, respectively, the nuclear and Coulomb potential. A comprehensive description of the formalism and parameterizations employed is presented in the following section. The half-life ($T_{1/2}$) and corresponding decay constant (λ) are determined using relations

$$T_{1/2} = \frac{\ln 2}{\lambda}, \lambda = \nu_o P_0 P. \quad (2.4)$$

Here, ν_o is the barrier assault frequency, calculated as

$$\nu_o = \frac{(2E_2/\mu)^{1/2}}{R_0}, \quad (2.5)$$

where R_0 denotes the nuclear radius, μ corresponds to the reduced mass and E_2 represents

the kinetic energy, defined as $E_2 = (A_1/A)Q$.

2.3.1 Coulomb Potential

The Coulomb interaction between two nuclear fragments constitutes an essential part of the total interaction potential governing the fission or decay dynamics of a nucleus. For the case of two mutually interacting spherical nuclei, the Coulomb interaction potential is given by $V_C(R) = \frac{Z_1 Z_2 e^2}{R}$. However, majority of nuclear fragments are deformed, so Coulomb potential must be modified to account for the influence of nuclear deformation parameters and orientation angles.

For the case of deformed and oriented nuclei, the expression for the Coulomb potential can be written as [?]:

$$V_C(Z_i, \beta_{\lambda i}, \alpha_i, \theta_i, T) = \frac{e^2 Z_1 Z_2}{R(T)} + 3e^2 Z_1 Z_2 \sum_{i=1,2}^{\lambda=2} \frac{1}{2\lambda+1} \frac{R_i^\lambda(\alpha_i, T)}{R(T)^{\lambda+1}} Y_\lambda^{(0)} \left[\beta_{\lambda i} + \frac{4}{7} \beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i) \right] \quad (2.6)$$

where $\beta_{\lambda i}$ represents the deformation parameter and θ_i denotes the orientation angle. The term $R_i(\alpha_i, T)$ corresponds to the effective radius of the i^{th} fragment. However, in this regime, the long-range Coulomb repulsion alone is insufficient to describe the total interaction potential, since the short-range attractive nuclear forces become significantly important. Therefore, to obtain the complete interaction potential between the two fragments, the nuclear interaction is essential and the same is discussed below.

2.3.2 Nuclear Potential

To further substantiate the expression given in Eq. 2.3, the second term represents nuclear potential. As discussed earlier, most commonly two approaches are used to calculate the nuclear potential. First is phenomenological potentials, those derived by Blocki *et al.* [? ? ? ? ? ? ? ?], are based on empirical models. The second approach employs microscopic potentials based on the Skyrme energy density formalism (SEDF) [? ? ?]. Such potentials provide a framework for understanding the nuclear forces governed during the complex interactions such as nuclear fusion, fission, and radioactive decay processes etc. [? ? ? ? ? ?]. In the present analysis, both phenomenological (Proximity 1977 and Proximity 1981) and microscopic approaches have been utilized to evaluate the nuclear

part of the interaction potential.

Proximity 1977

The nuclear proximity potential can be expressed as the product of two distinct functions: one determined by the geometrical properties of the interacting nuclei, and the other dependent on the surface separation distance “s” between them. between them. Its mathematical representation is given as [?]:

$$V_{Pij}(s) = f(sh., geo.)\phi(s) = 4\pi\bar{R}\gamma b\Phi(s). \quad (2.7)$$

In this expression, b (nuclear surface thickness) is taken as 0.99, while $\bar{R}$ represents the mean curvature radius of interacting nuclei. The quantity γ represents the nuclear energy coefficient, which given by $\gamma = \frac{1}{4\pi} [1 - 1.7826 [(N-Z)/A]^2] 0.9517 \text{ MeV fm}^{-2}$.

For deformed partners, the mean curvature radius ($\bar{R}$) is defined as:

$$\frac{1}{\bar{R}^2} = \frac{1}{R_{12}R_{11}} + \frac{1}{R_{22}R_{21}} + \frac{1}{R_{22}R_{11}} + \frac{1}{R_{12}R_{21}} \quad (2.8)$$

The principal radii of curvature $R_{11}, R_{22}, R_{12}, R_{21}$ are given by Balts and Bayman [?]. ϕ is the universal function that depends on the surface separation distance s and can be written as:

$$\phi(\xi) = -0.5(\xi - 2.54)^2 - 0.0852(\xi - 2.54)^3 \text{ and } -3.437 \exp\left[\frac{-\xi}{0.75}\right] \text{ respectively,}$$

for $\xi \leq 1.2511$ and $\xi \geq 1.2511$. Where $\xi = s/b$.

Proximity 1981

Proximity 1981 [?] can be given as:

$$V_{Pij}(\xi) = 4\pi \left(\frac{c_i c_j}{c_i + c_j} \right) \gamma b \Phi(\xi). \quad (2.9)$$

γ is taken the same as taken in Proximity 77. c_i is Sussman central radii. It is related to sharp radii as:

$$c_i = R_i - \left(\frac{b^2}{R_i} \right) \quad (2.10)$$

Where R_i is determined through a semi-empirical expression formulated in terms of the mass number A_i given as:

$$R_i = [1.28A_i^{\frac{1}{3}} - 0.76 + 0.8A_i^{\frac{1}{3}}]fm. \quad (2.11)$$

In Eqn. 2.9, the universal function $\Phi(\xi)$, depends on the distance between two nuclei and is given as:

$$\phi(\xi) = -1.7817 + 0.9270\xi + 0.0169\xi^2 - 0.05148\xi^3 \text{ and } -4.41\exp[\frac{-\xi}{0.7176}], \text{ respectively,}$$

for $\xi \leq 1.9475$ and $\xi \geq 1.9475$. Where $\xi = s/b$.

Skyrme energy density formalism (SEDF)

This section outlines the theoretical framework of the microscopic skyrme energy density formalism (SEDF) in conjunction with the semiclassical Extended Thomas–Fermi (ETF) approximation. Within this approach, the nuclear interaction potential $V_N(R)$ is evaluated as a function of the internuclear separation R using the Hartree–Fock (HF) method:

$$V_{Nij}(R) = E_{tot}(R) - E_i - E_j \quad (2.12)$$

where $E_{tot}(R)$ represents the total energy expectation value of parent nuclei. While E_i and E_j correspond to the individual energies of the decaying fragment. These energy expectation, E_{tot} , E_i and E_j are evaluated through volume integration of Hamiltonian density ($H(r)$) as:

$$E_{tot}(R) = \int \{H[\rho_n(\vec{r}), \rho_p(\vec{r})]d\vec{r}\}, \quad (2.13)$$

$$E_i(R) = \int \{H[\rho_{in}(\vec{r}), \rho_{ip}(\vec{r})]d\vec{r}\} \quad (i = 1, 2). \quad (2.14)$$

In this framework, $\rho_{in}(\vec{r})$, $\rho_{ip}(\vec{r})$ denote the proton and neutron densities of non-interacting nuclei. $\rho_n(\vec{r})$, $\rho_p(\vec{r})$ corresponds to those of the interacting nuclear system. The Skyrme energy density functional, $H(\vec{r})$ can be given as follows [?]:

$$H = K + H_0 + H_{den} + H_{eff} + H_{fin} + H_{so} + H_{tcsq}, \quad (2.15)$$

where $K = \frac{\hbar^2}{2m}\tau$ represents the kinetic energy term, while H_0 denotes zero-range term. The term H_{den} accounts for the density-dependent component, H_{eff} incorporates an effective-mass, The finite-range effects are included through H_{fin} , while H_{so} describes spin-orbit interaction and H_{tcsq} arises due to the tensor coupling with spin and gradient.

The skyrme Hamiltonian related to SIII [?] force can be written as:

$$\begin{aligned}
 H_0 &= \frac{1}{2}t_0 \left[\left(1 + \frac{1}{2}x_0\right) \rho^2 - \left(x_0 + \frac{1}{2}\right) (\rho_n^2 + \rho_p^2) \right], \\
 H_{den} &= \frac{1}{12}t_3\rho^{\alpha_0} \left[\left(1 + \frac{1}{2}x_3\right) \rho^2 - \left(x_3 + \frac{1}{2}\right) (\rho_n^2 + \rho_p^2) \right], \\
 H_{eff} &= \frac{1}{4} \left[t_1 \left(1 + \frac{1}{2}x_1\right) + t_2 \left(1 + \frac{1}{2}x_2\right) \right] \rho\tau \\
 &\quad - \frac{1}{4} \left[t_1 \left(x_1 + \frac{1}{2}\right) - t_2 \left(x_2 + \frac{1}{2}\right) \right] (\rho_n\tau_n + \rho_p\tau_p), \\
 H_{fin} &= \frac{1}{16} \left[3t_1 \left(1 + \frac{1}{2}x_1\right) - t_2 \left(1 + \frac{1}{2}x_2\right) \right] (\vec{\nabla}\rho)^2 \\
 &\quad - \frac{1}{16} \left[3t_1 \left(x_1 + \frac{1}{2}\right) + t_2 \left(x_2 + \frac{1}{2}\right) \right] \\
 &\quad \times \left[(\vec{\nabla}\rho_n)^2 + (\vec{\nabla}\rho_p)^2 \right], \\
 H_{so} &= -\frac{1}{2}W_0 \left[\rho\vec{\nabla} \cdot \vec{J} + \rho_n\vec{\nabla} \cdot \vec{J}_n + \rho_p\vec{\nabla} \cdot \vec{J}_p \right], \\
 H_{tcsg} &= -\frac{1}{16} (t_1x_1 + t_2x_2) \vec{J}^2 + \frac{1}{16} (t_1 - t_2) [\vec{J}_p^2 + \vec{J}_n^2].
 \end{aligned} \tag{2.16}$$

Here, $\vec{J} = \vec{J}_n + \vec{J}_p$, $\tau = \tau_n + \tau_p$ and $\rho = \rho_n + \rho_p$ denote the spin-orbit, kinetic energy and nuclear densities, respectively. x_j , t_j ($j=0-3$), α and W_0 are the Skyrme force parameters. Within the SEDF, the calculation of kinetic energy density $\tau(\rho)$, and spin-orbit density $\vec{J}(\rho)$ terms for composite systems can be classified in two ways, via frozen density approximations, as mentioned below.

Frozen density approximation:

$$\begin{aligned}
 \tau(\rho) &= \tau_1(\rho_1) + \tau_2(\rho_2), \\
 \vec{J}(\rho) &= \vec{J}_1(\rho_1) + \vec{J}_2(\rho_2).
 \end{aligned}$$

For the nuclear density ρ_i , the two-parameter Fermi (FD) distribution is employed, which is generalized to incorporate temperature dependence and is expressed as follows:

$$\rho_i(z_i) = \rho_{0i}(T) \left[1 + \exp \left(\frac{z_i - R_i(T)}{a_i(T)} \right) \right]^{-1}, \quad -\infty \leq z \leq \infty \tag{2.17}$$

with $z_2 = [R_1(\alpha_1) + R_2(\alpha_2) + s] - z_1$, and central density

$$\rho_{0i}(T) = \frac{3A_i}{4\pi R_i^3(T)} \left[1 + \frac{\pi^2 a_i^2(T)}{R_i^2(T)} \right]^{-1}. \quad (2.18)$$

$$R_{0i}(T) = [0.0994A_i - 9.8851 \times 10^{-4}A_i^2 + 4.8399 \times 10^{-6}A_i^3 - 8.4366 \times 10^{-9}A_i^4 + 0.9543] \quad (2.19)$$

Gupta *et al.* [?] formulated the slab approximation by considering semi-infinite nuclear matter with surfaces parallel to the x-y plane, moving in the z-direction. These surfaces are separated by distance s having minimum value s_0 . Under this approximation, the nuclear interaction potential $V_N(R)$ can be rewritten as

$$\begin{aligned} V_{Nij}(R) &= E_{tot}(R) - E_i - E_j = 2\pi\bar{R} \int_{s_0}^{\infty} \{H(\rho, \tau, \vec{J}) - [H_1(\rho_1, \tau_1, \vec{J}_1) + H_2(\rho_2, \tau_2, \vec{J}_2)]\} d\vec{r} \\ &= V_P(R) + V_J(R) \end{aligned} \quad (2.20)$$

The spin orbit independent part of the nuclear potential is given by

$$V_P(R) = \int_{s_0}^{\infty} \{H(\rho, \tau) - [H_1(\rho_1, \tau_1) + H_2(\rho_2, \tau_2)]\} d\vec{r}, \quad (2.21)$$

while the component arising from the spin-orbit interaction is expressed as

$$V_J(R) = \int_{s_0}^{\infty} \{H(\rho, \vec{J}) - [H_1(\rho_1, \vec{J}_1) + H_2(\rho_2, \vec{J}_2)]\} d\vec{r}. \quad (2.22)$$

2.3.3 Penetration Probability

Further, the barrier penetration probability P is evaluated using WKB approximation and can be written as:

$$P = P_a W_i P_b. \quad (2.23)$$

The total penetrability is evaluated in three successive steps, given as follows:

- (i) the penetrability P_a corresponding to barrier penetration from the inner turning point R_a to interaction radius R_i

$$P_a = \exp\left[-\frac{2}{\hbar} \int_{R_a}^{R_i} \{2\mu[V(R) - V(R_i)]\}^{1/2} dR\right], \quad (2.24)$$

- (ii) the inner de-excitation probability W_i at R_i [?],

$$W_i = \exp(-bE_i), \quad (2.25)$$

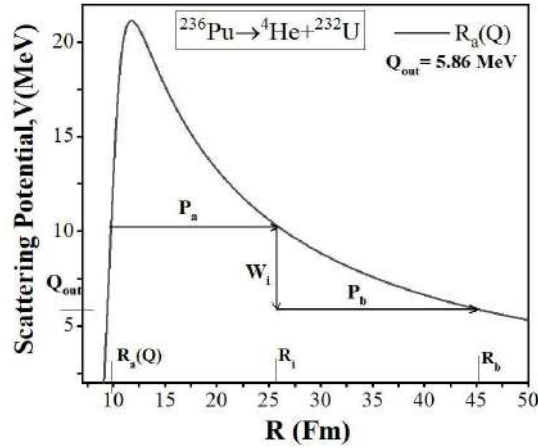


Figure 2.1: Scattering potential for the decay of ^{236}Pu for alpha using the $R_a(Q)$ [?].

(iii) the penetration probability P_b from R_i to R_b

$$P_b = \exp\left[-\frac{2}{\hbar} \int_{R_i}^{R_b} \{2\mu[V(R) - Q]\}^{1/2} dR\right]. \quad (2.26)$$

This three step penetration probability is illustrated in Fig. 2.1. $R=R_a$ is first (inner) turning point, whereas $R=R_b$ is second (outer) turning point calculated from the condition $V(R_b)=Q$ -Value. Thus, the quantum tunneling process initiates at R_a and terminates at R_b . The $R_a(Q)$ and $R_a(\Delta R)$ are the points obtained by using relation (discussed later in chapter 3). Here, the inner turning point R_a plays an important role for the decay analysis and calculated as $R_a = R_1 + R_2 + \Delta R$. The fragment radius can be calculated using:

$$R_i(\alpha_i) = R_{0i} \left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i) \right] \quad (2.27)$$

2.4 Three Cluster Model (TCM)

TCM [? ? ? ? ?] is an extension of PCM, specifically focusing on the three-body decay dynamics. In TCM, the decay process involves the emission of three fragments (clusters) from the parent nucleus. It is studied in terms of coordinates η and R . In ternary fission, three fragments are emitted with $A_1 \geq A_2 \geq A_3$. Until now, most of the work done by TCM is done by taking the decaying fragments as spherical [? ?]. In the present work, deformation effects are incorporated in fragments A_1 and A_2 , Where

the third fragment (A_3) is considered spherical. Deformations up to quadrupole (β_2) are included with consideration of optimum as well as specific-fixed orientations. For optimum orientations, θ_i are taken from ref [?] (see Table 1) i.e. hot-compact and cold-elongated configurations. The angles are uniquely fixed on the basis of signs of their corresponding quadrupole deformations [?]. The optimum orientations are of two types i.e. hot-compact (also referred to as the belly-to-belly configuration) and cold-elongated (also known as pole-to-pole configuration). Whereas, in fixed orientations, the values of θ are predetermined ($(90^0, 90^0), (0^0-0^0), (0^0-90^0)$ and (90^0-0^0)), independent of the choice of deformation signs. Fig 2.2(a), (b), (c), and (d) correspond to $(90^0, 90^0)$, $(0^0, 0^0)$, $(0^0, 90^0)$, and $(90^0, 0^0)$, respectively. Specifically where both β_{21} and β_{22} are ≥ 0 . Whereas, when both β_{21} and $\beta_{22} \leq 0$, then these configurations transform to: $(0^0, 0^0)$, $(90^0, 90^0)$, $(0^0, 90^0)$, and $(90^0, 0^0)$ respectively. Similarly for $\beta_{21} \geq 0$ and $\beta_{22} \leq 0$ these configurations transformed into $(90^0, 0^0)$, $(0^0, 90^0)$, $(90^0, 90^0)$, and $(0^0, 0^0)$ and vice versa true for $\beta_{21} \leq 0$ and $\beta_{22} \geq 0$. In this context, θ_i denotes the angular deviation between the collision and symmetry axis. Meanwhile, α_i specifies the angular deviation between the nuclear radius vector and its symmetry axis. It is important to note that θ_i is defined as being measured clockwise from the nuclear symmetry axis, whereas the rotational orientation α_i of each nucleus is measured in the counter clockwise direction from the collision z-axis.

One can calculate the fragmentation potential for the tripartition process and can be written as:

$$V_R(\eta, R) = \sum_{i=1}^3 \sum_{j>i}^3 B_i(A_i, Z_i) + V_{Cij}(R, Z_i, \beta_{\lambda i}, \theta_i, \phi) + V_{Pij}(R, A_i, \beta_{\lambda i}, \theta_i, \phi) \quad (2.28)$$

Where B_i are the binding energies of the fragments, taken from [? ?]. The potential V_{Cij} and V_{Pij} are Coulomb and proximity potential can be written as [? ? ?]:

$$V_{Cij}(Z_i, \beta_{\lambda i}, \theta_i, \alpha_i) = \frac{Z_i Z_j e^2}{R} + 3Z_i Z_j e^2 \sum_{\lambda, i=1,2} \frac{1}{2\lambda+1} \frac{R_i^\lambda(\alpha_i)}{R^{\lambda+1}} Y_\lambda^{(0)}(\theta_i) \left[\beta_{\lambda i} + \frac{4}{7} \beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i) \right] \quad (2.29)$$

$$V_{Nij}(\xi) = 4\pi \bar{R} \gamma b \Phi(s) \quad (2.30)$$

Here, in Eqn. 2.29, $e^2 = 1.44$ Mev fm. The relative separation between any two participating nuclei i and j ($i, j = 1, 2, 3$) is:

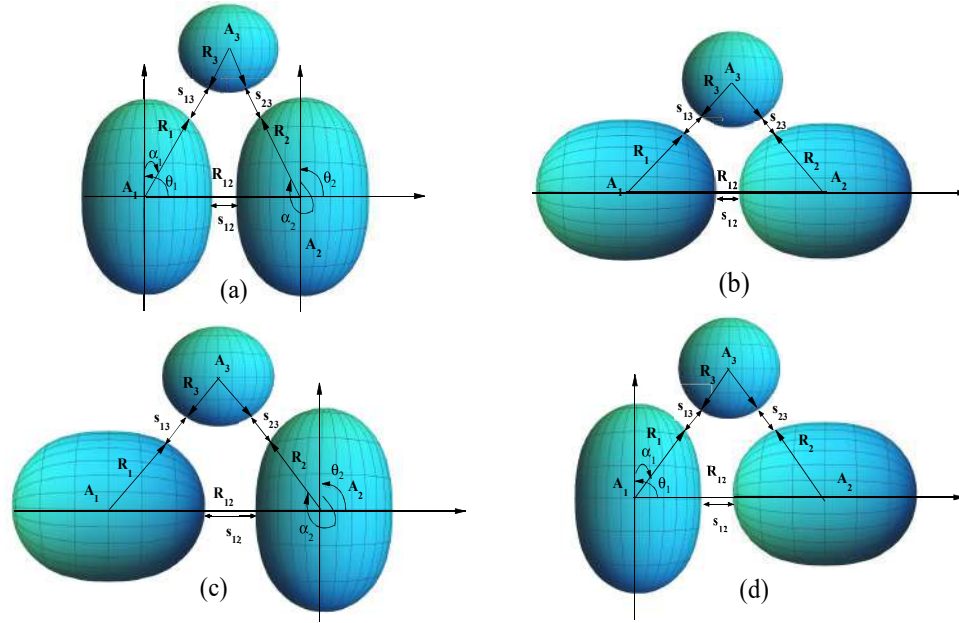


Figure 2.2: Schematic diagram of an equatorial configuration of two deformed heavy nuclei (A_1 and A_2) with the spherical third fragment ($A_3=^4\text{He}$) $(\theta_1, \theta_2) =$ (a) $90^\circ-90^\circ$ (b) $0^\circ-0^\circ$ (c) $0^\circ-90^\circ$ (d) $90^\circ-0^\circ$ with $\beta_{21}, \beta_{22} \geq 0$.

$$R_{ij} = R_i + R_j + s_{ij} \quad (2.31)$$

where R_i represents the radius vector (shown in Eqn. 2.27) of fragments represented in Fig. 2.2. Here, R_{0i} is

$$R_{0i} = [1.28A_i^{\frac{1}{3}} - 0.76 + 0.8A_i^{\frac{1}{3}}]fm. \quad (2.32)$$

In this context “ s_{ij} ” represents the relative separation between the fragments as shown in Fig. 2.3. The value of this parameter is influenced by the arrangement of three specific fragments, namely ECT and CCT as shown in Fig. 2.3. In ECT, the surface separation distance between each fragment can be expressed by [? ?]:

$$s_{12} = s_{23} = s_{31} = s \quad (2.33)$$

whereas for CCT the surface separation is [?]

$$s_{12} = 2(R_3 + s), s_{23} = s_{31} = s \quad (2.34)$$

In Eqn. 2.30, the universal function $\Phi(s)$, depends only on the distance between two nuclei as discussed earlier. For various formulations of the proximity potential, corresponding $\Phi(s)$ can be adopted. Further, the penetration probability of three-body decay channel is

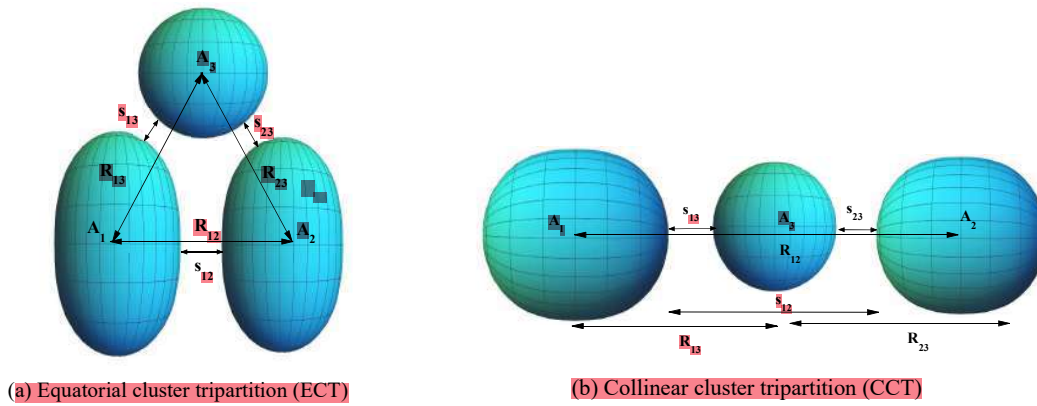


Figure 2.3: (a) ECT (b) CCT configurations of two deformed heavy nuclei (A_1 and A_2) with the spherical third fragment. R_{ij} denotes the center-to-center distance between two nuclei and s_{ij} represents the corresponding surface-to-surface separation distance between them.

estimated as

$$P = \exp\left[-\frac{2}{\hbar} \int_{s_1}^{s_2} \{2\mu[V(R) - Q]\}^{1/2} ds\right]. \quad (2.35)$$

Here, s_1 and s_2 are the first and second turning points satisfying the $V(s_2) = Q$ (Q-value).

μ is the reduced mass of the three fragments,

$$\mu_{123} = \left(\frac{\mu_{12} A_3}{\mu_{12} + A_3} \right) m, \quad (2.36)$$

where $\mu_{12} = A_1 A_2 / (A_1 + A_2)$ and m is the nucleon mass.

Furthermore, the relative yields corresponding to the various fragmentation channels in ternary decay processes are determined by taking the ratio of the penetration probability of a specific fragment combination to the cumulative penetration probabilities of all energetically allowed fragment combinations, expressed as follows:

$$Y(A_i, Z_i) = \frac{P(A_i, Z_i)}{\sum P(A_i, Z_i)} \quad (2.37)$$

Moreover, the model has been extended [?] to encompass the phenomenon wherein two charged particles are emitted from the neck of the radioactive nuclei, termed as quaternary fission. It is studied in terms of mass-asymmetry coordinate (η) and relative separation (s). In quaternary fission, four fragments are emitted with $A_1 \geq A_2 \geq A_3 \geq A_4$. Here, the third and fourth fragments represented as A_3 and A_4 are fixed, and hence mass

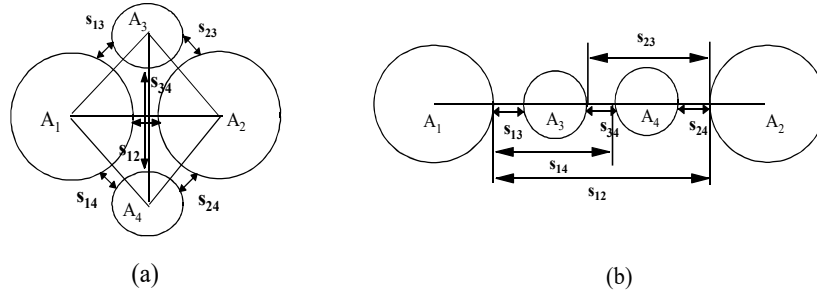


Figure 2.4: Quaternary fission of ^{252}Cf in (a) equatorial configuration and (b) Collinear configuration.

and charge asymmetry is considered between A_1 and A_2 . Therefore, the fragmentation potential for four emitted fragments can be written as:

$$V_R(\eta, R) = \sum_{i=1}^4 \sum_{j>i}^4 B_i(A_i, Z_i) + V_{Cij}(R, Z_i, \theta_i, \phi) + V_{Pij}(R, A_i, \theta_i, \phi) \quad (2.38)$$

The relative separation among the four fragments c_{ij} is taken as Eqn. 2.10. s_{ij} is the surface separation between decaying fragments of four fragments, as shown in Fig. 2.4(a-b). The configuration in which the third and fourth fragments are emitted perpendicular to the fission axis is shown in Fig. 2.4(a), while emission along the fission axis is shown in Fig. 2.4(b). In the present study, the analysis has been conducted under the assumption of spherical nuclear shapes. The relative distance between the center of the fragments is taken as

$$c_{12} = c_1 + c_2 + s_{12}, \quad (2.39)$$

$$c_{13} = c_1 + c_3 + s_{13}, \quad (2.40)$$

$$c_{14} = c_1 + c_4 + s_{14}, \quad (2.41)$$

$$c_{23} = c_2 + c_3 + s_{23}, \quad (2.42)$$

$$c_{24} = c_2 + c_4 + s_{24}, \quad (2.43)$$

$$c_{34} = c_3 + c_4 + s_{34}, \quad (2.44)$$

Therefore, the surface separation distance (Fig. 2.4(a)) for equatorial configuration is given as:

$$s_{12} = s_{13} = s_{23} = s_{24} = s_{14} = s \quad (2.45)$$

In addition to this, s_{34} is calculated as

$$s_{34} = c_{34} - c_3 - c_4 \quad (2.46)$$

where c_3 and c_4 are calculated from

$$c_i = R_i - \frac{b^2}{R_i} \quad (2.47)$$

and intermediate segment c_{34} is computed via Heron's formula, based on the known side lengths of the triangle. The height of each constituent triangle (upper and lower as shown in fig. 6.2(a)) is evaluated from the corresponding area. This height corresponds to give length c_{34} .

On the other hand, the configuration mode where the third and fourth fragments are emitted along with the fission axis is known as the collinear configuration, as shown in fig.6.2(b). The surface separation distance between the fragments for the collinear configuration is written as:

$$\begin{aligned} s_{12} &= (2c_3 + 2c_4 + 3s), s_{14} = 2c_3 + 2s, \\ s_{23} &= 2c_4 + 2s, s_{13} = s_{24} = s_{34} = s \end{aligned} \quad (2.48)$$

Further, the penetration probability of decay channel is estimated as given in Eqn. 2.35.

It must be noted here that, μ is the reduced mass of the four fragments given as:

$$\mu_{1234} = \left(\frac{\mu_{123} A_4}{\mu_{123} + A_4} \right) m, \quad (2.49)$$

Where, μ_{123} is defined in Eqn. 2.36. Further relative yield corresponding to fragmentation channel is calculated by taking the ratio of penetration probability of a given channel over the sum of penetration probabilities of all possible channels given in Eqn. 2.37.

2.5 Dynamical Cluster Decay Model

The Preformed Cluster Model (PCM) and the Three-Cluster Model (TCM) are employed to investigate the ground-state decay mechanisms of radioactive nuclei. In such ground-state processes, the influence of temperature and angular momentum is generally negligible;

hence, these parameters are considered “silent” in the theoretical treatment. To extend this understanding toward the description of heavy-ion-induced reactions, where both temperature (T) and angular momentum play a crucial role. The Dynamical Cluster-decay Model (DCM) [? ?] has been developed as a modified and temperature-dependent extension of the PCM.

The fission cross-sections ($\sigma_{\text{fis}}^{\text{Theo}}$) can be determined for the possible fission fragments, for both the mass as well as charge distributions, respectively, as

$$\begin{aligned}\sigma_{\text{fis}}^{\text{Theo}}(A_1, A_2) &= \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) P P_0(\eta_A), \text{ here, } A_2 = \frac{A_{\text{CN}}}{2} \pm 30, A_1 = A_{\text{CN}} - A_2, \\ \sigma_{\text{fis}}^{\text{Theo}}(Z_1, Z_2) &= \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) P P_0(\eta_Z), \text{ here, } Z_2 = \frac{Z_{\text{CN}}}{2} \pm 10, Z_1 = Z_{\text{CN}} - Z_2.\end{aligned}\quad (2.50)$$

In the above equations, A_i (and Z_i) and A_{CN} (and Z_{CN}) are the mass (and charge) numbers of fragment i and CN, respectively. $k = \sqrt{\frac{2\mu E_{\text{c.m.}}}{\hbar^2}}$ is the wave vector and $\mu = m[A_1 A_2 / (A_1 + A_2)]$.

It is crucial to emphasize that, in the aforementioned relation, the product of penetration P and preformation P_0 probabilities is summed up to ℓ_{max} . The maximum values of ℓ for the available range of incident energies $E_{\text{c.m.}}$ are identified at a point beyond which the contribution of the light particles no longer contributes.

In Eq. (2.50), the term ‘ P ’ represents the barrier penetration probability. It corresponds to the quantum mechanical tunneling of the preformed fragments through the interaction barrier. The penetration process begins at the first turning point R_a (first turning point), and terminate through the R_b (second turning point), such that $V(R_a) = V(R_b)$. A visual representation of the total interaction potential as a function of separation distance R is presented in Fig. 2.5. The penetrability P is evaluated using WKB approximation [?] and is expressed as follows:

$$P = \exp \left[-\frac{2}{\hbar} \int_{R_a}^{R_b} \{2\mu[V(R) - Q_{\text{eff}}]\}^{1/2} dR \right]. \quad (2.51)$$

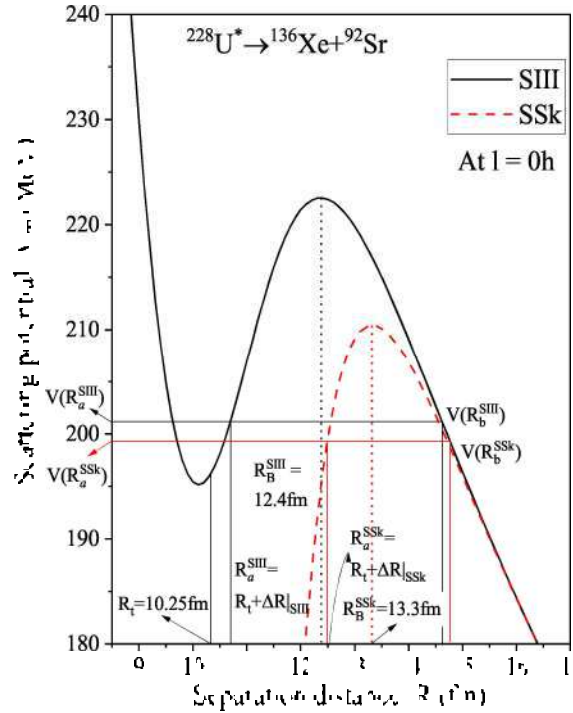


Figure 2.5: The scattering potential V_T (MeV) varying as a function of separation distance R (fm) between the centers of two emitting fragments derived using two Skyrme forces, i.e. SIII [?] and SSk [?], is shown here for exit channel ($^{228}\text{U}^* \rightarrow ^{136}\text{Xe} + ^{92}\text{Sr}$) [?].

From Fig. 2.5, one can see that two different Skyrme forces (SIII [?] and SSk [?]) influence the barrier characteristics (barrier height, barrier position and barrier curvature) significantly, henceforth the choice of tunneling points get changed. In the above equation, ‘ Q_{eff} ’ enotes the effective Q-value associated with the specific decay channel, and it is defined as follows:

$$Q_{eff}(T) = B(T) - B_1(0) - B_2(0), \quad (2.52)$$

where B_1 and B_2 are the binding energies of the decaying fragments. Here, the temperature-dependent binding energy [?] is defined as:

$$B_i(T) = \sum_{i=1}^2 V_{\text{LDM}} + \sum_{i=1}^2 [\delta U_i] \exp \left[-\frac{T^2}{T_0} \right]. \quad (2.53)$$

Here, $i = 1, 2$ denotes fragment 1 and fragment 2, respectively. $V_{\text{LDM}}(T, Z_i, A_i)$ represents the temperature dependent liquid drop energy as formulated by Davidson *et al* [? ? ?]. The subsequent contribution i.e. shell-corrections is given by Myers and Swiatecki [?] with its T - dependence from Davidson *et al* [?]. The above equations are obtained through following statistical relation [?]

$$E_{\text{CN}}^* = \frac{1}{9} AT^2 - T. \quad (2.54)$$

Further, on the basis of QMFT, the stationary Schrodinger equation solved in η_A [?] and η_Z [?] coordinates defines P_0 . For η_A , the P_o is given by Eq. 2.2 and for η_Z it is given as:

$$P_0(\eta_Z) = |\psi(\eta(Z_i))|^2 \sqrt{B_{\eta_Z \eta_Z}} \frac{2}{Z_{CN}}. \quad (2.55)$$

In these equations, the possible outcomes of the vibrational states $\psi(\eta(A_i))$ and $\psi(\eta(Z_i))$ are associated with excitations to higher vibrational modes. These are assumed to follow Boltzmann-like wave functions, presented in [?].

$$|\psi|^2 = \sum_{\nu=0}^{\infty} |\psi^{\nu}|^2 \exp(E^{\nu}/T), \quad (2.56)$$

here, ν ($= 0, 1, 2, 3, 4, \dots$) is the quantum number. The smooth hydro-dynamical parameters $B_{\eta_A \eta_A}$ and $B_{\eta_Z \eta_Z}$ are defined as [?]:

$$B_{\eta\eta} = \frac{AmR^2}{4} \left[\frac{\nu_t(1+\gamma)}{\nu_c(1+\delta^2)} - 1 \right]. \quad (2.57)$$

The $\psi^{\nu}(\eta)$ is expanded in terms of the stationary harmonic oscillator wave functions [?], as given below:

$$\psi(\nu, t=0) = \exp(ik_o\eta) \exp\left(-(\eta - \eta_i)^2/2\sigma^2\right). \quad (2.58)$$

In the Schrodinger equation of η -coordinate [? ?], $V(\eta)$ of decaying fragments is used and defined as

$$V_R(\eta, T) = \sum_{i=1}^2 B_i(T) + V_{\ell}(R, A_i, \beta_{\lambda i}, \theta_i, T) + V_C(R, Z_i, \beta_{\lambda i}, \theta_i, T) + V_N(R, A_i, \beta_{\lambda i}, \theta_i, T). \quad (2.59)$$

The constituents of scattering potential $V_T(R)$, i.e. centrifugal potential (V_{ℓ}), Coulomb potential (V_C) and nuclear potential (V_N), are dependent on R , A_i (and Z_i), $\beta_{(\lambda i)}$ and θ_i factors. On the other hand, the nuclear potential $V_N(R, A_i, \beta_{\lambda i}, \theta_i, T)$ (or simply $V_N(R)$) in this study is derived using the semiclassical approach of Skyrme Energy Density Formalism and the relation of effective nuclear potential is given below [? ? ?].

$$V_N(R) = 2\pi\bar{R} \times \int_s^{\infty} \left[H(\rho, \tau, \vec{J}) - H(\rho_1, \tau_1, \vec{J}_1) - H(\rho_2, \tau_2, \vec{J}_2) \right] ds. \quad (2.60)$$

Here, $s = R - R_1 - R_2$ denotes the separation distance between two interacting fragments. In the above relation, the Hamiltonians dependent on the nuclear density ρ , kinetic energy

density τ and spin-orbit density $\vec{J}$ [1, 2] terms. Numerous parameterizations of the Skyrme effective interaction have been developed in the literature [3, 4, 5, 6, 7, 8, 9, 10, 11]. Each version is characterized by a distinct set of coupling constants defining various nuclear properties of nuclei.

CHAPTER 3

Study of various ground state decay mechanisms of Actinide nuclei

3.1 Introduction

After the description of general introduction and methodology in chapters 1 and 2, I plan to discuss the results in the subsequent chapters. The chapter 3 is described to the various ground state decay modes analysed within the scope of methodology used in this thesis. The radioactive emission includes different decay modes such as γ -decay, β -decay, α -decay, CR, HPR and SF [? ? ? ? ? ? ? ? ? ?]. These decay modes are generally found in the nuclei belonging to the heavy mass region [? ?]. One of the interesting property of such nuclei is that they can decay via one or multiple channels of the above mentioned decay modes. Therefore, it is important to analyse these decay modes in terms of different nuclear properties such as shape, size, magicity, the decay constant, or the decay half-lives [? ?] etc. Different theoretical and experimental approaches [? ? ? ? ? ? ? ? ? ? ? ? ?] were employed to explore such decay modes. Numerous theoretical models such as ASAFM [? ? ?], UFM [? ? ? ? ?], PCM [? ? ? ?], DDCM [? ?], TPA [? ? ?], GLDM [? ? ?] and many other approaches [? ? ?] are introduced which successfully explain the radioactive emission of a variety of fragments.

In ASAFM, the decay half-life and decay constant are calculated using the penetration probability (P) and the assault frequency (ν_o). The preformation hypothesis is not exercised in ASAFM. Using this model, it had been studied [?] that the decay half-lives strongly depend on the Q-value of the decay channel and it is observed that 5-10% change in the Q-value alters the half-lives by a order of magnitude. The preformation (P_o) and penetration (P) effects are incorporated in ref. [?] using pre and post-touching regions

of the decaying fragments and their Q -value dependent relations are obtained. One may note that the P_o and P depend on the Q -value of the decay channel and consequently effect the decay half-lives [?]. The preformed cluster model (PCM) explores different ground state mechanisms and is based on the collective mass clusterization approach, where the probable binary fragments are treated on parallel footing [? ?]. In view of this, γ and β - decay are not studied using this model.

In general the stability analysis of radioactive nuclei is worked out in terms of decay constant and the decay half-life. As discussed earlier, the Q -value of given decay channel plays an important role in the calculation of P_o and P . Hence in the present work, P_o and P are calculated at the Q -value dependent R_a point, i.e., $R_a(Q)$. In previous work of our group [?], the spontaneous fission properties of some 45 nuclei were studied, where the most probable spontaneous fission channels were identified. The present study includes a comparative analysis between α -decay and SF using a new set of binding energies [?]. Additionally α , CR and HPR modes are analysed by incorporating the Q -value effects in first turning point R_a . The aim of the present study is to (i) set Q -value dependent relation ($R_a(Q)$) for α decay, CR and HPR modes and to explore the behaviour of associated properties. (ii) preformation probability, penetration probability and $\log T_{1/2}$ of the nuclei using above mentioned $R_a(Q)$ values. (iii) carry out spontaneous fission mass distribution analysis using the spherical and hot configuration of the β_2 -deformed fragments. (iv) study the TKE of fission fragments. The related calculations and results are discussed in Section 3.2. Additionally, emphasis is focused on identifying and characterizing the rare yet physically significant 2α decay mode. The study aims to understand the isotopic evolution of decay modes, particularly the transition from dominant α decay to the emergence of simultaneous 2α and the heavier cluster emissions. Hence, the aim is to understand the structural and dynamical conditions that prefer the simultaneous 2α emission and identify specific isotopes where such processes become increasingly probable. The even-odd staggering observed in reference to the calculated decay half-lives and preformation probabilities reflects the underlying nuclear structure effects and pairing correlations, offering additional insight into decay dynamics. The conclusions derived from these observations are summarized and discussed in Section 3.3. The research work

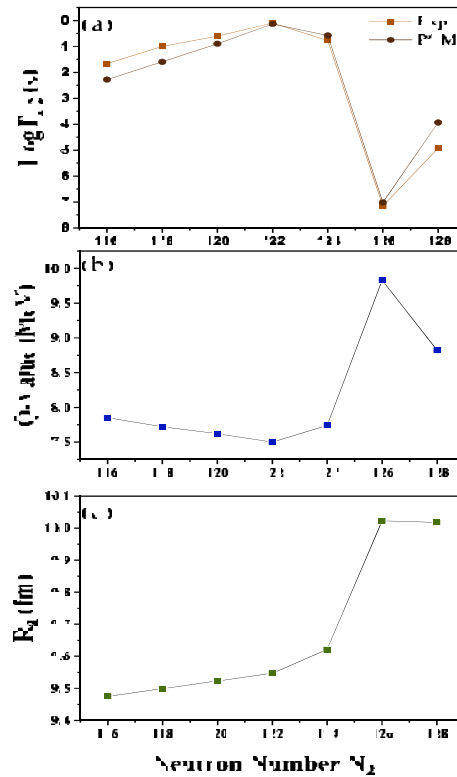


Figure 3.1: Variation of (a) PCM calculated logarithmic half-lives for α decay and the experimental data, as a function of neutron number (N_2) of daughter nucleus. (b) Q-value for alpha decay (c) variation of first turning point $R_a(=R_1+R_2+\Delta R)$

presented in this chapter has been published in Ref. [? ?].

3.2 Calculations and Results

This chapter represents the theoretical investigation of different ground state decay mechanisms (α , CR, HPR and SF) using PCM for nuclei having $Z=89-102$. First, in Section 3.2.1, the Q-value dependent first turning point $R_a(Q)$ is obtained and alpha decay analysis of the chosen set of isotopes is made using this relation. The overall trend of P_o and P are analyzed as a function of mass of the parent and the daughter nucleus. In Section 3.2.2 and 3.2.3, the decay half-lives are estimated for cluster radioactivity and the heavy particle radioactivity using $R_a(Q)$ of the respective mode, and a comparison is made with the available literature. Finally, the spontaneous fission analysis is made in Section 3.2.4.

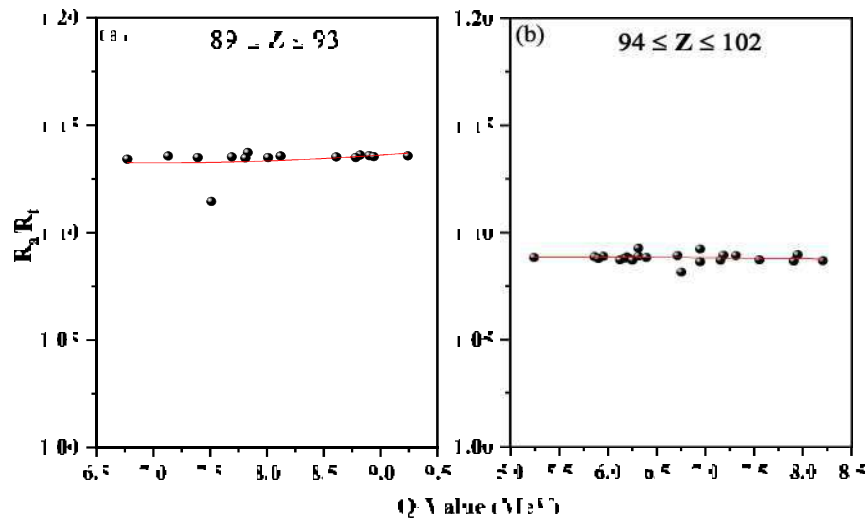


Figure 3.2: The variation of R_a/R_t with respect to Q_α for chosen set of nuclei (a) $Z=89-93$ (b) $Z=94-102$, the fitted polynomial corresponds to solid line.

3.2.1 α decay study of the actinide nuclei

In this section, α decay analysis of the actinide nuclei belonging to actinide region is carried out using the PCM. It will be of interest to explore the alpha decay mechanism and study its behaviour with respect to increase in mass or neutron number of parent nucleus. The α disintegration from a radioactive parent nucleus is the emission of a stable α nucleus along with a complementary daughter. The shell closure effects associated with the parent or the daughter nucleus are the main reason for the radioactive disintegration. The final product of radioactive disintegration is basically the decaying fragments associated with nearby proton or neutron shell closure. Hence, the shell effects significantly affect alpha decay or other radioactive decay mechanisms (CR, HPR and SF) and the associated decay constant or the decay half-lives.

As a first step, α decay half-lives of actinium isotopes (^{207}Ac , ^{209}Ac , ^{211}Ac , ^{213}Ac , ^{215}Ac , ^{217}Ac , ^{221}Ac) are calculated. Using the optimum choice of neck length parameter (ΔR). In reference to available data the comparison between the calculated and experimental half-lives [?] is made and shown in Fig. 3.1.(a). The calculated $\log T_{1/2}$ -values show good agreement with the available experimental data. Figure shows that the decay half-life for $N=128$ (with daughter nucleus $N_2=126$) has least half-life as compared to the other isotopes. The nuclei are more stable due to neutron shell closure effect. After the decay

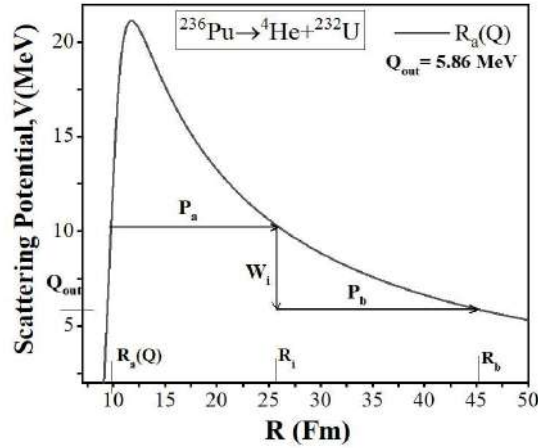


Figure 3.3: Scattering potential for the decay of ^{236}Pu for alpha using the $R_a(Q)$.

half-lives, the Q -value of the decay channel i.e. Q_α is plotted with respect to N_2 and shown in Fig. 3.1.(b). One may note from the figure that the Q_α has the highest magnitude for the nucleus with $N=128$ ($N_2=126$) as compared to its neighbouring nuclei (shell closure effect). In the prior investigation of PCM [?], it was found that the relative separation R and the neck length parameter ΔR play a key role in the determination of different decay properties associated with the radioactive nuclei. The calculations of preformation probability and the barrier penetrability are carried out at R_a , which is the sum of R_t and ΔR i.e. $R_a=R_t+\Delta R$. Hence, to observe the role of first turning point, the R_a point is plotted with respect to N_2 shown in Fig. 3.1(c). It may be noted that the R_a has highest magnitude at $N_2=126$, in accordance with Q_α and the decay half-life effect. This study motivates to obtain a Q -value dependent R_a relation i.e. $R_a(Q)$. Hence, to make $R_a(Q)$ two ranges of nuclei $Z=89-93$ and $Z=94-102$ are opted and a graph is made between the ratio (R_a/R_t) and the Q_α as shown in Fig. 3.2(a) and (b), where R_t is the sum of radii R_1 and R_2 . The R_a points here are calculated by fitting $\log T_{1/2}$ with respect to the available experimental data [? ?]. Hence, using Fig. 3.2(a) and (b) we can get the polynomials $R_a^\alpha(Q)$ for the two ranges of the nuclei.

$$R_a^\alpha(Q) = R_t(A_1 + A_2Q_\alpha - A_3Q_\alpha^2) \quad 89 \leq Z \leq 93 \quad (3.1)$$

$$R_a^\alpha(Q) = R_t(B_1 + B_2Q_\alpha - B_3Q_\alpha^2) \quad 94 \leq Z \leq 102 \quad (3.2)$$

Where $A_1=1.10413$, $A_2=0.00768$, $A_3=4.65 \times 10^{-4}$ and similarly constants for heavier

3.2 Calculations and Results

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Table 3.1: Calculated values of point R_a with $R_a(\Delta R)$ and $R_a^\alpha(Q)$ using Eqs. (3.1,3.2) for lighter and heavier set of nuclei. The comparison of the half-lives is shown by using $R_a(\Delta R)$ and $R_a^\alpha(Q)$ with experimental data [? ?].

Parent nucleus	Decay channel	$R_a(\Delta R)$ (fm)	$R_a^\alpha(Q)$ (fm)	$\log T_{1/2}[R_a(\Delta R)]$ (sec)	$\log T_{1/2}[R_a^\alpha(Q)]$ (sec)	$\log T_{1/2}(s)$ (Exp.)
Z = 89-93						
^{212}Ac	$^4\text{He}+^{208}\text{Fr}$	9.73	9.89	0.00	-0.03	-0.02
^{219}Ac	$^4\text{He}+^{215}\text{Fr}$	10.01	10.01	-3.93	-3.93	-4.92
^{222}Ac	$^4\text{He}+^{218}\text{Fr}$	10.05	10.02	2.28	2.23	0.73
^{213}Th	$^4\text{He}+^{209}\text{Ra}$	9.94	9.91	-0.80	-0.84	-0.85
^{220}Th	$^4\text{He}+^{216}\text{Ra}$	10.02	10.02	-4.91	-4.91	-5.01
^{222}Th	$^4\text{He}+^{218}\text{Ra}$	10.05	10.03	-2.11	-2.12	-2.55
^{221}Pa	$^4\text{He}+^{217}\text{Ac}$	10.04	10.05	-4.99	-5.00	-5.23
^{224}Pa	$^4\text{He}+^{220}\text{Ac}$	10.07	10.05	1.03	1.00	-0.10
^{225}Pa	$^4\text{He}+^{221}\text{Ac}$	10.08	10.06	1.07	1.03	0.38
^{223}U	$^4\text{He}+^{219}\text{Th}$	10.06	10.06	-2.78	-2.78	-4.74
^{224}U	$^4\text{He}+^{220}\text{Th}$	10.07	10.07	-3.44	-3.44	-3.05
^{225}U	$^4\text{He}+^{221}\text{Th}$	10.08	10.07	0.24	0.21	-1.00
^{225}Np	$^4\text{He}+^{221}\text{Pa}$	10.08	10.08	-3.20	-3.21	>-5.7
^{227}Np	$^4\text{He}+^{223}\text{Pa}$	10.11	10.09	-0.15	-0.14	-0.29
^{230}Np	$^4\text{He}+^{226}\text{Pa}$	10.14	10.12	5.22	5.24	≤ 3.96
Z = 94-102						
^{228}Pu	$^4\text{He}+^{224}\text{U}$	9.72	9.70	-0.01	0.16	-0.70
^{230}Pu	$^4\text{He}+^{226}\text{U}$	9.74	9.73	2.75	2.80	≥ 2.30
^{232}Pu	$^4\text{He}+^{228}\text{U}$	9.76	9.75	4.85	4.88	4.20
^{234}Pu	$^4\text{He}+^{230}\text{U}$	9.78	9.78	6.71	6.74	5.72
^{235}Pu	$^4\text{He}+^{231}\text{U}$	9.80	9.79	8.91	8.91	7.75
^{236}Pu	$^4\text{He}+^{232}\text{U}$	9.81	9.80	8.93	8.93	8.11
^{239}Pu	$^4\text{He}+^{235}\text{U}$	9.84	9.84	12.63	12.63	12.00
^{232}Am	$^4\text{He}+^{228}\text{Np}$	9.76	9.75	3.72	3.77	3.59
^{237}Am	$^4\text{He}+^{233}\text{Np}$	9.82	9.82	7.70	7.70	7.18
^{240}Cm	$^4\text{He}+^{236}\text{Pu}$	9.85	9.85	7.24	7.24	6.52
^{242}Cm	$^4\text{He}+^{238}\text{Pu}$	9.87	9.88	8.40	8.41	7.28
^{243}Cm	$^4\text{He}+^{239}\text{Pu}$	9.88	9.89	9.21	9.21	8.96
^{244}Cm	$^4\text{He}+^{240}\text{Pu}$	9.89	9.90	9.89	9.89	8.88
^{250}Cf	$^4\text{He}+^{246}\text{Cm}$	9.96	9.97	9.87	9.87	8.69
^{252}Cf	$^4\text{He}+^{248}\text{Cm}$	9.98	9.99	9.71	9.71	8.00
^{251}Es	$^4\text{He}+^{247}\text{Bk}$	10.02	9.98	9.33	9.32	7.48
^{253}Es	$^4\text{He}+^{249}\text{Bk}$	9.94	10.00	7.73	7.63	6.30
^{254}Es	$^4\text{He}+^{250}\text{Bk}$	10.05	10.01	9.12	9.13	7.38
^{250}Fm	$^4\text{He}+^{246}\text{Cf}$	9.96	9.97	3.96	3.90	<3.30
^{252}Fm	$^4\text{He}+^{248}\text{Cf}$	9.98	9.99	5.73	5.71	5.04
^{255}Md	$^4\text{He}+^{251}\text{Es}$	10.01	10.02	3.28	3.24	3.21
^{260}Md	$^4\text{He}+^{256}\text{Es}$	10.06	10.08	8.64	8.62	>6.98
^{254}No	$^4\text{He}+^{250}\text{Fm}$	10.00	10.01	2.28	2.28	1.86

3.2 Calculations and Results

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Table 3.2: PCM-calculated alpha decay half-lives $\text{Log}T_{1/2}$ for 31 nuclei for $Z = 89-93$.

Parent nucleus	Decay channel	Q_α (MeV)	R_a^α (Fm) (Poly.)	$\text{log}T_{1/2}$ (s) (Poly.)	$\text{log}T_{1/2}$ (s) ASAFM [?]	$\text{log}T_{1/2}$ (s) ELDM [?]	$\text{log}T_{1/2}$ (s) (Exp) [?]
^{207}Ac	$^4\text{He}+^{203}\text{Fr}$	7.84	9.82	-3.62	3.30	-1.60	-1.66
^{208}Ac	$^4\text{He}+^{204}\text{Fr}$	7.72	9.84	-1.18	4.50	-1.16	-1.02
^{209}Ac	$^4\text{He}+^{205}\text{Fr}$	7.72	9.85	-2.78	-	-1.18	-1.00
^{210}Ac	$^4\text{He}+^{206}\text{Fr}$	7.60	9.86	-0.41	-	-0.80	-0.44
^{211}Ac	$^4\text{He}+^{207}\text{Fr}$	7.62	9.88	-2.06	-	-0.88	-0.60
^{213}Ac	$^4\text{He}+^{209}\text{Fr}$	7.49	9.90	-1.15	-	-0.48	-0.10
^{215}Ac	$^4\text{He}+^{211}\text{Fr}$	7.74	9.93	-1.33	-	-1.36	-0.77
^{217}Ac	$^4\text{He}+^{213}\text{Fr}$	9.83	10.02	-6.94	-6.90	-6.99	-7.16
^{218}Ac	$^4\text{He}+^{214}\text{Fr}$	9.37	10.02	-4.19	-6.50	-5.96	-7.16
^{210}Th	$^4\text{He}+^{206}\text{Ra}$	8.06	10.01	-3.91	-	-1.85	-5.96
^{212}Th	$^4\text{He}+^{208}\text{Ra}$	7.95	9.89	-3.41	-1.20	-1.57	-1.52
^{214}Th	$^4\text{He}+^{210}\text{Ra}$	7.82	9.92	-2.10	-0.80	-1.19	-1.00
^{216}Th	$^4\text{He}+^{212}\text{Ra}$	8.07	9.95	-2.73	-1.50	-2.00	-1.55
^{218}Th	$^4\text{He}+^{214}\text{Ra}$	9.85	10.03	-7.37	-	-6.71	-6.96
^{219}Th	$^4\text{He}+^{215}\text{Ra}$	9.51	10.03	-4.66	-5.96	-	-5.96
^{224}Th	$^4\text{He}+^{220}\text{Ra}$	7.29	10.05	1.08	0.00	0.43	0.11
^{226}Th	$^4\text{He}+^{222}\text{Ra}$	6.45	10.07	4.85	3.30	3.79	3.38
^{228}Th	$^4\text{He}+^{224}\text{Ra}$	5.52	10.12	9.53	7.90	8.38	7.92
^{230}Th	$^4\text{He}+^{226}\text{Np}$	4.76	10.17	14.13	12.50	13.05	12.49
^{232}Th	$^4\text{He}+^{228}\text{Ra}$	4.08	10.22	19.41	-	18.45	17.76
^{213}Pa	$^4\text{He}+^{209}\text{Ac}$	8.39	9.92	-4.22	-	-2.53	-2.28
^{214}Pa	$^4\text{He}+^{210}\text{Ac}$	8.27	9.93	-2.04	-	-2.19	≥ -1.77
^{215}Pa	$^4\text{He}+^{211}\text{Ac}$	8.24	9.94	-3.48	-1.80	-2.12	-1.82
^{216}Pa	$^4\text{He}+^{212}\text{Ac}$	8.09	9.95	-1.36	1.30	-1.68	-0.54
^{217}Pa	$^4\text{He}+^{213}\text{Ac}$	8.48	9.97	-3.43	-2.30	-2.89	-2.47
^{218}Pa	$^4\text{He}+^{214}\text{Ac}$	9.80	10.03	-5.32	-3.70	-6.25	-3.74
^{219}Pa	$^4\text{He}+^{215}\text{Ac}$	10.09	10.06	-7.59	-6.90	-6.92	-7.28
^{220}Pa	$^4\text{He}+^{216}\text{Ac}$	9.65	10.05	-4.65	-5.50	-6.37	-6.11
^{227}Pa	$^4\text{He}+^{223}\text{Ac}$	6.58	10.09	4.67	3.70	3.68	3.73
^{218}U	$^4\text{He}+^{214}\text{Th}$	8.77	9.99	-4.54	-	-3.35	-2.82
^{222}U	$^4\text{He}+^{218}\text{Th}$	9.43	10.07	-5.97	-	-5.27	-6.00
^{226}U	$^4\text{He}+^{222}\text{Th}$	7.70	10.08	-0.02	-0.30	-0.21	-0.70
^{228}U	$^4\text{He}+^{224}\text{Th}$	6.80	10.10	3.73	2.90	3.17	< 2.76
^{229}U	$^4\text{He}+^{225}\text{Th}$	6.47	10.11	6.34	4.30	4.57	4.43
^{230}U	$^4\text{He}+^{226}\text{Th}$	5.99	10.13	7.83	6.40	6.85	6.43
^{233}U	$^4\text{He}+^{229}\text{Th}$	4.90	10.20	14.63	12.70	13.18	12.77
^{226}Np	$^4\text{He}+^{222}\text{Pa}$	8.19	10.08	0.03	-	-1.37	-1.15
^{228}Np	$^4\text{He}+^{224}\text{Pa}$	7.30	10.10	2.86	-	1.23	2.18
^{229}Np	$^4\text{He}+^{225}\text{Pa}$	7.01	10.11	3.38	2.30	2.78	< 2.66
^{231}Np	$^4\text{He}+^{227}\text{Pa}$	6.36	10.14	6.45	5.40	5.52	5.18

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Table 3.3: PCM-calculated alpha decay half-lives $\text{Log}T_{1/2}$ for 32 nuclei for $Z = 94-102$.

Parent nucleus	Decay channel	Q_α (MeV)	R_α^α (fm) (Poly.)	$\text{log}T_{1/2}$ (s) (Poly.)	$\text{log}T_{1/2}$ (s) ASAFM [?]	$\text{log}T_{1/2}$ (s) ELDM [?]	$\text{log}T_{1/2}$ (s) (Exp.) [?]
^{233}Pu	$^4\text{He}+^{229}\text{U}$	6.41	9.77	7.00	5.80	5.72	6.00
^{238}Pu	$^4\text{He}+^{234}\text{U}$	5.59	9.83	10.73	9.50	9.88	9.59
^{240}Pu	$^4\text{He}+^{236}\text{U}$	5.25	9.85	12.42	11.40	11.88	11.45
^{242}Pu	$^4\text{He}+^{238}\text{U}$	4.98	9.88	14.08	-	13.64	13.18
^{238}Cm	$^4\text{He}+^{234}\text{Pu}$	6.67	9.83	5.63	4.90	5.64	≥ 4.93
^{246}Cm	$^4\text{He}+^{242}\text{Pu}$	5.47	9.92	12.34	-	11.50	11.26
^{248}Cm	$^4\text{He}+^{244}\text{Pu}$	5.16	9.95	14.48	-	13.46	13.15
^{250}Cm	$^4\text{He}+^{246}\text{Pu}$	5.16	9.97	14.68	-	13.38	12.45
^{240}Cf	$^4\text{He}+^{236}\text{Cm}$	7.71	9.85	2.30	-	2.00	1.81
^{242}Cf	$^4\text{He}+^{238}\text{Cm}$	7.51	9.87	3.24	2.40	2.70	2.41
^{244}Cf	$^4\text{He}+^{240}\text{Cm}$	7.32	9.90	3.96	3.10	3.43	3.18
^{246}Cf	$^4\text{He}+^{242}\text{Cm}$	6.86	9.92	5.97	-	5.34	5.20
^{248}Cf	$^4\text{He}+^{244}\text{Cm}$	6.36	9.95	8.52	-	7.63	7.54
^{251}Cf	$^4\text{He}+^{247}\text{Cm}$	6.17	9.98	10.68	10.90	8.52	10.45
^{254}Cf	$^4\text{He}+^{250}\text{Cm}$	5.92	10.02	11.27	9.30	9.79	9.30
^{256}Cf	$^4\text{He}+^{252}\text{Cm}$	5.56	10.04	13.48	-	11.90	10.87
^{252}Es	$^4\text{He}+^{248}\text{Bk}$	6.78	9.99	9.67	7.60	5.99	7.61
^{245}Fm	$^4\text{He}+^{241}\text{Cf}$	8.43	9.99	1.73	-	0.28	0.62
^{246}Fm	$^4\text{He}+^{242}\text{Cf}$	8.37	9.91	0.80	-	0.50	0.08
^{248}Fm	$^4\text{He}+^{244}\text{Cf}$	7.99	9.94	2.16	-	1.70	1.65
^{254}Fm	$^4\text{He}+^{250}\text{Cf}$	7.30	10.01	5.61	4.10	4.22	4.15
^{256}Fm	$^4\text{He}+^{252}\text{Cf}$	7.02	10.04	6.79	5.10	5.36	5.15
^{247}Md	$^4\text{He}+^{243}\text{Es}$	8.76	9.92	-0.10	-	-0.86	0.46
^{256}Md	$^4\text{He}+^{252}\text{Es}$	7.73	10.03	5.28	3.90	2.36	3.66
^{257}Md	$^4\text{He}+^{253}\text{Es}$	7.55	10.05	5.02	3.70	3.60	4.30
^{258}Md	$^4\text{He}+^{254}\text{Es}$	7.27	10.06	7.96	5.80	4.73	6.65
^{259}Md	$^4\text{He}+^{255}\text{Es}$	7.10	10.07	7.10	-	5.39	> 5.28
^{250}No	$^4\text{He}+^{246}\text{Fm}$	8.94	9.96	-0.32	-	-0.65	-0.30
^{252}No	$^4\text{He}+^{248}\text{Fm}$	8.54	9.98	1.00	-	0.58	0.62
^{255}No	$^4\text{He}+^{251}\text{Fm}$	8.42	10.02	1.33	2.80	0.88	2.27
^{256}No	$^4\text{He}+^{252}\text{Fm}$	8.58	10.03	1.58	0.50	0.41	0.56
^{258}No	$^4\text{He}+^{254}\text{Fm}$	8.14	10.05	3.10	1.70	1.83	2.08

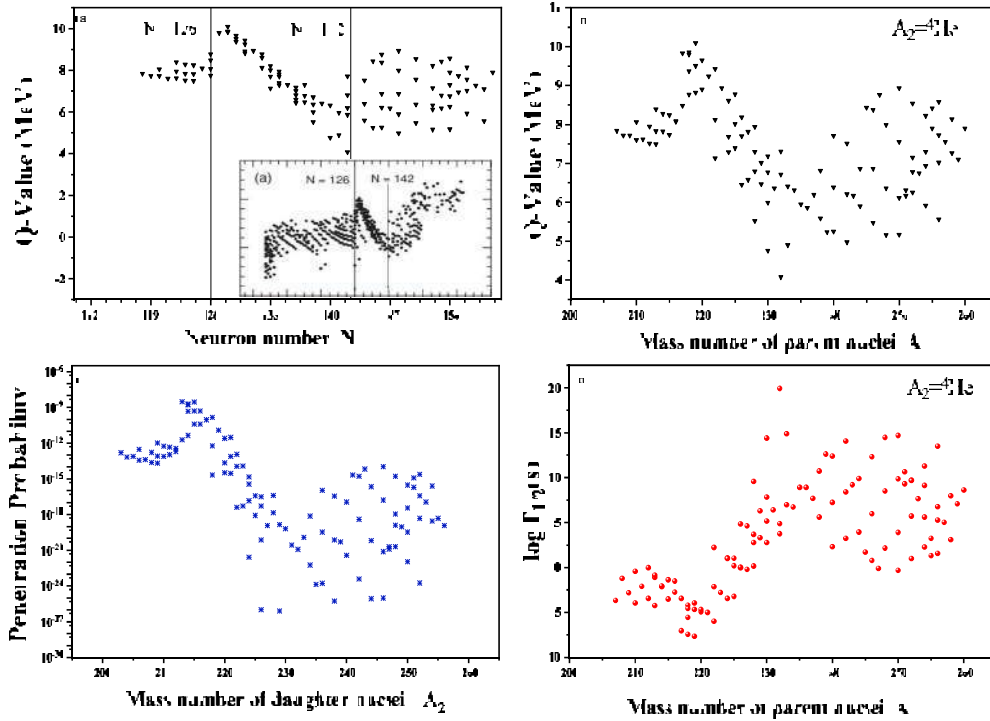


Figure 3.4: The calculated (a) Q_α as a function of N (neutron number of parent nucleus), the inset of figure is taken from ref. [?]. The scale of x axis and y-axis represent same quantities for both the graphs (i.e. Q_α and N) of parent nucleus, (b) Q_α as a function of mass number, (c) Penetration probability P with respect to A_2 , (d) decay half-lives with respect to A . All the above values are calculated for α decay data using $R_a(Q)$ relations(Eqs. 3.1,3.2).

nuclei are $B_1=1.08702$, $B_2=6.657 \times 10^{-4}$, $B_3=7.184 \times 10^{-5}$. Hence one may use Eqs. (3.1) and (3.2) to calculate the R_a point respectively for the lighter and heavier nuclei. The validation of above $R_a(Q)$ relations (eqs. 3.1 and 3.2) is made by calculating the alpha decay half-lives of the same set of lighter and heavier nuclei. The comparison of both kind of R_a points i.e. $R_a(\Delta R)$ and $R_a^\alpha(Q)$ is made in Table 3.1.

In order to see the relevance of the polynomial Eqs. (3.1 and 3.2), in the context of alpha decay within PCM, the standard rms deviation is calculated by using the equation:

$$\sigma = \sqrt{\sum [\log_{10}(T_i/T_{expt.})]^2 / n - 1} \quad (3.3)$$

where n is the total number of parent nuclei in the consideration. The standard deviation of the decay half-lives using Eqs. (3.1 and 3.2) is 1.14 and 1.05 respectively, where as we get 1.15 and 1.05 for optimized ΔR values. Further the scattering potential of

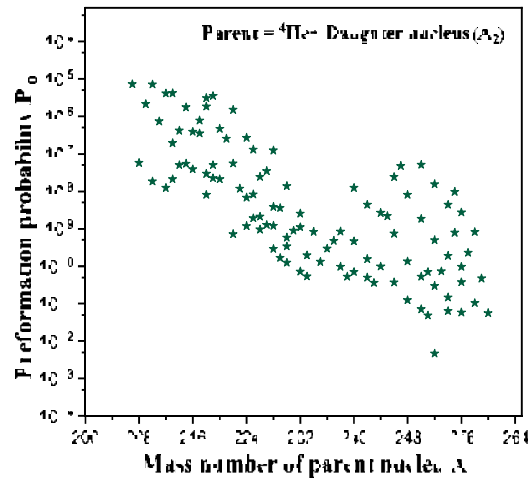


Figure 3.5: The PCM calculated α preformation probability for 109 nuclei ($Z=89-102$) as a function of the mass number of the parent nucleus.

^{236}Pu is plotted with respect to internuclear separation distance R by taking R_a point from Q dependent relation (Eq. (3.2)) and the one shown in Fig. 3.3. We have also compared the R_a point by taking optimum choice of ΔR and got almost similar result. Hence, one may use these Q -dependent relation to calculate the decay half-lives of a radioactive nuclei as they provide a good approximation with experimental data. After this, the investigation of several nuclei is carried out from $Z=82-93$ and $Z=94-102$, and a comparison between the half-life calculated using $R_a^\alpha(Q)$ and the experimental values is made and shown in Table 3.2 and Table 3.3. It can be seen from these tables that calculated decay half-lives using $R_a^\alpha(Q)$ relation shows consistent results with the experimental data except for a few cases. The deviation are observed in the periphery of the neutron-deficient and neutron-rich isotopes. These isotopes may exhibit deviations from the predicted decay half-lives due to specific nuclear structure effects and underlying physics. Also, these results are compared with the observations of other theoretical models i.e. ASAFM [?] and ELDM [?]. Which further shows a reasonable agreement. Hence, Eqs. (3.1 and 3.2) can be used to give an adequate account of half life values. After calculating the decay half-lives, the overall trend of the Q -value, P , P_o , and $\log T_{1/2}$ is studied, in reference to obtained $R_a^\alpha(Q)$ relation. In Fig. 3.4.(a) calculated Q_α using $R_a^\alpha(Q)$ relation is plotted against neutron number of parent nuclei. At $N=128$ ($N_2=126$) the Q_α is maximum due to the shell closure effects. Such nuclei are relatively unstable so they have higher Q -value

and decay rate is relatively faster. Further as one approaches towards $N=142$ i.e. away from shell closure, Q_α start decreasing and this trend is compared with Fig. 1.(a) of ref. [?] shown in inset of 3.4.(a). Further in Fig. 3.4.(b) the Q_α decreases sharply around $A=217-235$. This is due to the effect of neutron shell closure of daughter nuclei for $A=217-219$ ($N=128, N_2=126$) and start decreasing as we move away from the shell closure. It may be noted that there exist few stable nuclei (against alpha decay) at mass number $A \geq 230$ (here the Q -value is about 4MeV and respective half-life is very large 10^{19}). Beyond this, Q_α start increasing and this may be due to the presence of next shell closure after $N_2=126$. Further, the penetration probability P is calculated and shown in Fig. 3.4.(c). The penetration probability (a three step process explain in Eq.(2.23)) and role of Q_α in penetrability can be visualised from Fig. 3.3. The penetration probability is maximum for $A_2=213-215$ ($N_2=126$), so it is easier for the alpha particle to escape across these daughter nuclei. This is due to the neutron shell closure at $N=126$. After the analysis of Q_α and the penetrability, the PCM calculated alpha decay $\log T_{1/2}$ are plotted with respect to mass number A in Fig. 3.4.(d). The decay half-lives depend on decay constant which further depend on assault frequency(nearly constant), penetration probability and preformation probability. Here, penetration probability start decreasing till $A=217$ and then sharply increases between $A=217-235$. This is due to the influence of shell effects as mentioned earlier. From this figure one can observe that as the mass number of parent nuclei increases, the preformation factor decreases. A similar analysis of preformation probability is done by using GLDM model for α decay in ref. [?].

3.2.2 Analysis of cluster emission

In the previous section, alpha decay of different nuclei was worked out using $R_a^\alpha(Q)$ relation and the calculated $\log T_{1/2}$ were found in good agreement with the available data. In the present section, study of the cluster emission is made by using $R_a^{CR}(Q)$ relation. Previously in ref. [? ?], cluster decay analysis was made using older mass tables or proximity potentials within the framework of the PCM. It is important to mention that the present calculations are performed using mass table of Audi *et al.* 2017 [?]. The decay half-lives are calculated for the experimentally observed clusters by the optimization

of the neck length parameter ΔR and the appropriate value of the R_a point is fixed. The obtained $R_a^{CR}(Q)$ value is further used to get the $R_a(Q)$ relation by using the same procedure (for both spherical and the deformed decaying fragments) as mentioned in the previous section for α decay case. The $R_a(Q)$ relations for CR process read as:

$$R_a^{CR}(Q) = R_t(C_1 - C_2 Q_{cluster} + C_3 Q_{cluster}^2) \quad (3.4)$$

for spherical choice of decay fragments, whereas for the β_2 -deformed case, it is given as:

$$R_a^{CR}(Q) = R_t(D_1 - D_2 Q_{cluster} + D_3 Q_{cluster}^2) \quad (3.5)$$

$Q_{cluster}$ is the q-value of the decay channel. In Eq. (3.4), $C_1=1.05502$, $C_2=1.17016 \times 10^{-4}$ and $C_3=3.424 \times 10^{-7}$. and similarly constants for Eq. (3.5) are $D_1=1.0573$, $D_2=2.07598 \times 10^{-4}$, $D_3=8.8151 \times 10^{-7}$. The Eq. (3.4) and Eq. (3.5) can be employed to give the decay $\log T_{1/2}$ in a cluster decay mechanism. The validity of these equations can be tested by comparing the results with experimental data. The comparison between the decay half-lives obtained using the $R_a^{CR}(Q)$ relation and the corresponding experimental values, for both spherical and deformed configurations of the decaying fragments, is presented in Table 3.4. In this table, R_a^{CR} is obtained using $R_a^{CR}(Q)$ relation. It may be noted from the table that the calculated R_a^{CR} points and corresponding decay half-lives shows consistent results with experimental data. It has been observed that the deformed choice shows relatively better agreement (as compared to the spherical case) with the experimental data. In addition to this, to check the validity of the polynomials used, the standard deviation (SD) is calculated with respect to the experimental results. For the spherical choice the SD are 4.20 and 4.21 for R_a^{CR} and $R_a^{CR}(Q)$. Hence the spherical clusters don't impart good agreement. After analysing the spherical choice, the SD is calculated for the deformed choice of clusters, which are 2.75 and 2.77 for R_a^{CR} and $R_a^{CR}(Q)$. Further, the calculated half-lives are compared with data of theoretical models i.e. (ASAFM) [?] and mean-field approximation in the Hartree-Fock-Bogoliubov (HFB) [?], which shows a reasonable agreement with the predicted data. Similar to the alpha decay analysis, the scattering plot for cluster radioactivity of ^{236}Pu is shown in Fig. (3.6). Then, the first turning point

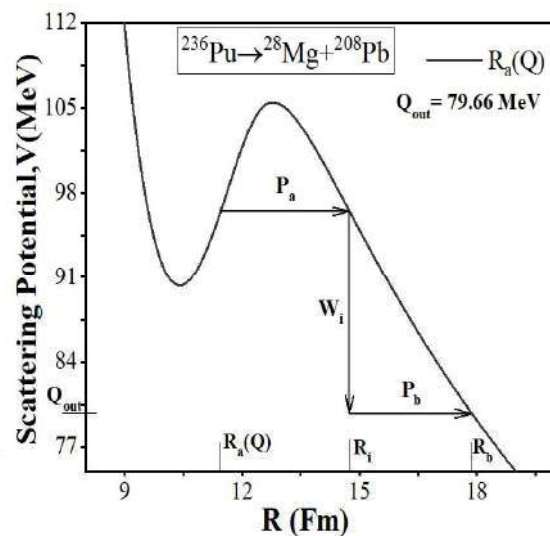


Figure 3.6: Scattering potential for the decay of ^{236}Pu for cluster radioactivity using the $R_a(Q)$.

is compared by taking optimum choice of ΔR .

Therefore, it is clear from the above calculations that SD is reduced for deformed choice of fragments. Therefore polynomial in Eq. (3.5) gives a reasonable approximation and can be used to calculate the decay half-lives of the clusters emitted from actinide nuclei.

3.2.3 Heavy Particle Radioactivity

After the analysis of the α decay and cluster emission, the study of heavy particle radioactivity is made in this section. In previous study [? ?], our group have predicted $\log T_{1/2}$ of the heavy clusters emitted by certain heavy nuclei. In this work, I have extended the previous work to the full range of actinide series. The HPR results are shown in Table 3.5. Here, the most probable heavy fragments are determined by the minima in the fragmentation potential. The calculated Q-values of the decay channel i.e. Q_{HPR} and the decay half-lives are also shown in Table 3.5. The $R_a^{HPR}(Q)$ for HPR case is given as:

$$R_a^{HPR} = R_t(E_1 + E_2 Q_{HPR} - E_3 Q_{HPR}^2) \quad (3.6)$$

Where $E_1=0.9484$, $E_2=3.055 \times 10^{-4}$, $E_3=7.867 \times 10^{-7}$ Calculations of first turning point (R_a) by taking optimum value of parameter ΔR and using Eq. (3.6) are shown in column 4 and 5 respectively. The half lives are represented in last two column. The predicted fragments are isotopes of Ge as these nuclei show shell effects around $N=50$. These heavy

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Table 3.4: A comparison of the decay half-lives for various experimentally observed clusters is carried out with those calculated within the PCM framework using the Prox-1977 potential for both spherical and deformed configurations of the participating nuclei. The corresponding cluster Q-values, $Q_{cluster}$ are evaluated using the binding energies reported by Audi *et al.* [?] for each decay channel.

Parent nucleus	Decay Channel	$Q_{cluster}$ (MeV)	PCM						Expt.
			Spherical		Deformed		ASAFM	HFB	
			$R_a^{CR}(\text{fm})$ (Poly.)	$\log T_{1/2}(s)$ (Poly.)	$R_a^{CR}(\text{fm})$ (Poly.)	$\log T_{1/2}(s)$ (Poly.)	$\log T_{1/2}(s)$ [?]	$\log T_{1/2}(s)$ [?]	
^{223}Ac	$^{14}\text{C} + ^{209}\text{Bi}$	33.06	10.12	17.06	10.16	14.77	12.7	–	12.60
^{223}Ac	$^{15}\text{N} + ^{208}\text{Pb}$	39.47	10.17	18.85	10.17	16.91	14.1	–	>14.76
^{225}Ac	$^{14}\text{C} + ^{211}\text{Bi}$	30.47	10.15	21.54	10.19	20.77	17.8	–	17.16
^{226}Th	$^{14}\text{C} + ^{212}\text{Po}$	30.54	10.16	22.29	10.18	21.26	17.7	–	>15.3
^{226}Th	$^{18}\text{O} + ^{208}\text{Pb}$	45.72	10.35	22.43	10.37	21.70	18.0	17.31	>15.3
^{228}Th	$^{20}\text{O} + ^{208}\text{Pb}$	44.72	10.47	23.54	10.48	22.79	21.9	19.53	20.87
^{230}Th	$^{24}\text{Ne} + ^{206}\text{Hg}$	57.76	10.64	26.90	10.70	25.96	25.2	25.08	24.61
^{231}Pa	$^{23}\text{F} + ^{208}\text{Pb}$	51.88	10.62	25.25	10.86	24.29	25.9	–	26.02
^{231}Pa	$^{24}\text{Ne} + ^{207}\text{Tl}$	60.40	10.65	23.37	10.71	22.65	23.3	–	23.23
^{230}U	$^{22}\text{Ne} + ^{208}\text{Pb}$	61.38	10.56	23.90	11.22	20.70	20.4	20.49	19.57
^{230}U	$^{24}\text{Ne} + ^{206}\text{Pb}$	61.81	10.64	23.09	10.69	22.28	22.4	–	>18.2
^{232}U	$^{24}\text{Ne} + ^{208}\text{Pb}$	62.30	10.66	21.09	10.72	20.28	20.8	23.35	21.05
^{232}U	$^{28}\text{Mg} + ^{204}\text{Hg}$	74.31	10.79	26.01	11.52	21.91	–	–	>22.26
^{233}U	$^{24}\text{Ne} + ^{209}\text{Pb}$	60.48	10.68	25.77	10.76	24.76	25.2	–	24.84
^{233}U	$^{25}\text{Ne} + ^{208}\text{Pb}$	60.70	10.71	25.08	10.82	24.15	25.7	–	24.84
^{233}U	$^{28}\text{Mg} + ^{205}\text{Hg}$	74.22	10.81	27.50	11.42	24.26	27.4	–	>27.59
^{234}U	$^{24}\text{Ne} + ^{210}\text{Pb}$	58.82	10.69	28.26	10.74	27.14	26.1	27.24	25.92
^{234}U	$^{25}\text{Ne} + ^{209}\text{Pb}$	57.79	10.73	29.49	10.86	28.31	28.8	–	25.92
^{234}U	$^{26}\text{Ne} + ^{208}\text{Pb}$	59.41	10.76	26.39	11.02	24.93	27.0	28.02	25.92
^{234}U	$^{28}\text{Mg} + ^{206}\text{Hg}$	74.11	10.82	26.81	11.42	23.35	25.9	25.85	25.54
^{235}U	$^{24}\text{Ne} + ^{211}\text{Pb}$	57.36	10.70	32.16	10.76	30.24	–	–	27.62
^{235}U	$^{25}\text{Mg} + ^{210}\text{Pb}$	57.68	10.74	45.97	10.84	29.20	–	–	27.62
^{235}U	$^{28}\text{Mg} + ^{207}\text{Hg}$	72.42	10.83	30.66	11.46	26.32	–	–	>28.09
^{235}U	$^{29}\text{Mg} + ^{206}\text{Hg}$	72.46	10.86	30.38	11.37	26.61	–	–	>28.09
^{236}U	$^{28}\text{Mg} + ^{208}\text{Hg}$	70.73	10.85	32.37	11.45	28.45	–	33.68	27.58
^{236}U	$^{30}\text{Mg} + ^{206}\text{Hg}$	72.27	10.91	28.78	11.17	26.46	29.8	33.1	27.58
^{238}U	$^{34}\text{Si} + ^{204}\text{Pt}$	85.18	11.04	30.63	11.02	29.85	–	–	29.04
^{237}Np	$^{30}\text{Mg} + ^{207}\text{Tl}$	74.79	10.92	26.41	11.18	23.88	28.3	–	>26.93
^{236}Pu	$^{28}\text{Mg} + ^{208}\text{Pb}$	79.66	10.84	20.36	11.45	16.19	21.1	20.13	21.67
^{238}Pu	$^{28}\text{Mg} + ^{210}\text{Pb}$	75.91	10.87	26.94	11.48	22.65	26.2	29.42	25.70
^{238}Pu	$^{30}\text{Mg} + ^{208}\text{Pb}$	76.79	10.93	24.48	11.19	22.02	26.2	29.52	25.70
^{238}Pu	$^{32}\text{Si} + ^{206}\text{Hg}$	91.18	10.98	25.25	11.12	22.84	26.1	28.23	25.27
^{240}Pu	$^{34}\text{Si} + ^{206}\text{Hg}$	91.02	11.06	24.57	11.05	22.73	27.4	26.96	>25.52
^{241}Am	$^{34}\text{Si} + ^{207}\text{Tl}$	93.92	11.07	21.80	11.06	20.16	25.8	–	>22.71
^{242}Cm	$^{34}\text{Si} + ^{208}\text{Pb}$	96.50	11.08	19.44	11.07	17.98	23.5	24.9	23.24
^{252}Cf	$^{46}\text{Ar} + ^{206}\text{Hg}$	126.75	11.48	16.41	11.66	14.98	26.5	–	>15.89
^{252}Cf	$^{48}\text{Ca} + ^{204}\text{Pt}$	138.17	11.52	18.61	11.52	18.27	–	–	>15.89
^{252}Cf	$^{50}\text{Ca} + ^{202}\text{Pt}$	138.31	11.56	17.73	11.71	15.95	–	–	>15.89

Table 3.5: PCM calculated half-life for heavy particle Radioactivity of Z ranging 89-102 parent systems. The choice of outgoing fragment is based on most probable fragment having highest preformation probability. Note that in each case spherical choice of fragments is considered and calculations with $l = 0\hbar$ and $T = 0$ MeV only with optimized ΔR as -0.25 is set of all the isotopes.

Parent nucleus	Decay channel	Q_{HPR} (MeV)	R_a^{HPR} (Poly.)	$\log T_{1/2}(s)$ Poly.
^{232}U	$^{82}\text{Ge} + ^{150}\text{Nd}$	173.70	10.92	30.32
^{234}U	$^{82}\text{Ge} + ^{152}\text{Nd}$	173.71	10.95	30.54
^{236}U	$^{82}\text{Ge} + ^{154}\text{Nd}$	173.68	10.98	29.40
^{238}U	$^{82}\text{Ge} + ^{156}\text{Nd}$	173.19	11.01	30.07
^{240}Pu	$^{82}\text{Ge} + ^{158}\text{Sm}$	180.79	11.04	28.07
^{242}Pu	$^{82}\text{Ge} + ^{160}\text{Sm}$	180.36	11.07	28.19
^{244}Pu	$^{82}\text{Ge} + ^{162}\text{Sm}$	179.75	11.10	28.32
^{246}Pu	$^{82}\text{Ge} + ^{164}\text{Sm}$	178.90	11.12	28.93
^{238}Cm	$^{84}\text{Se} + ^{154}\text{Sm}$	198.75	11.03	23.05
^{240}Cm	$^{84}\text{Se} + ^{156}\text{Sm}$	197.03	11.05	24.00
^{242}Cm	$^{84}\text{Se} + ^{158}\text{Sm}$	196.00	11.08	25.27
^{244}Cm	$^{82}\text{Ge} + ^{162}\text{Gd}$	188.14	11.10	25.85
^{246}Cm	$^{82}\text{Ge} + ^{164}\text{Gd}$	187.80	11.12	26.06
^{248}Cm	$^{82}\text{Ge} + ^{166}\text{Gd}$	187.33	11.15	25.93
^{250}Cm	$^{82}\text{Ge} + ^{168}\text{Gd}$	186.76	11.18	26.37
^{244}Cf	$^{84}\text{Se} + ^{160}\text{Gd}$	205.36	11.11	21.37
^{246}Cf	$^{84}\text{Se} + ^{162}\text{Bk}$	204.30	11.14	22.26
^{248}Cf	$^{84}\text{Se} + ^{164}\text{Gd}$	202.95	11.17	23.55
^{250}Cf	$^{82}\text{Ge} + ^{168}\text{Dy}$	195.14	11.18	24.07
^{252}Cf	$^{82}\text{Ge} + ^{170}\text{Dy}$	195.10	11.20	23.68
^{254}Cf	$^{82}\text{Ge} + ^{172}\text{Dy}$	194.76	11.23	22.71

clusters are not yet experimentally detected, therefore these observations may impart useful insight for future validations.

3.2.4 Comparative analysis of alpha decay and spontaneous fission (SF)

In the previous sections, an analysis of α emission, CR and HPR is made using respective $R_a(Q)$ relations. It is concluded that the first turning point plays a crucial role in exploring the dynamics of these decay modes. It is known that the α decay and SF are the most observed decay modes. In this section, a comprehensive analysis is made among the α decay and SF modes using PCM. In Fig. 3.7, the comparison between the fragmentation

3.2 Calculations and Results

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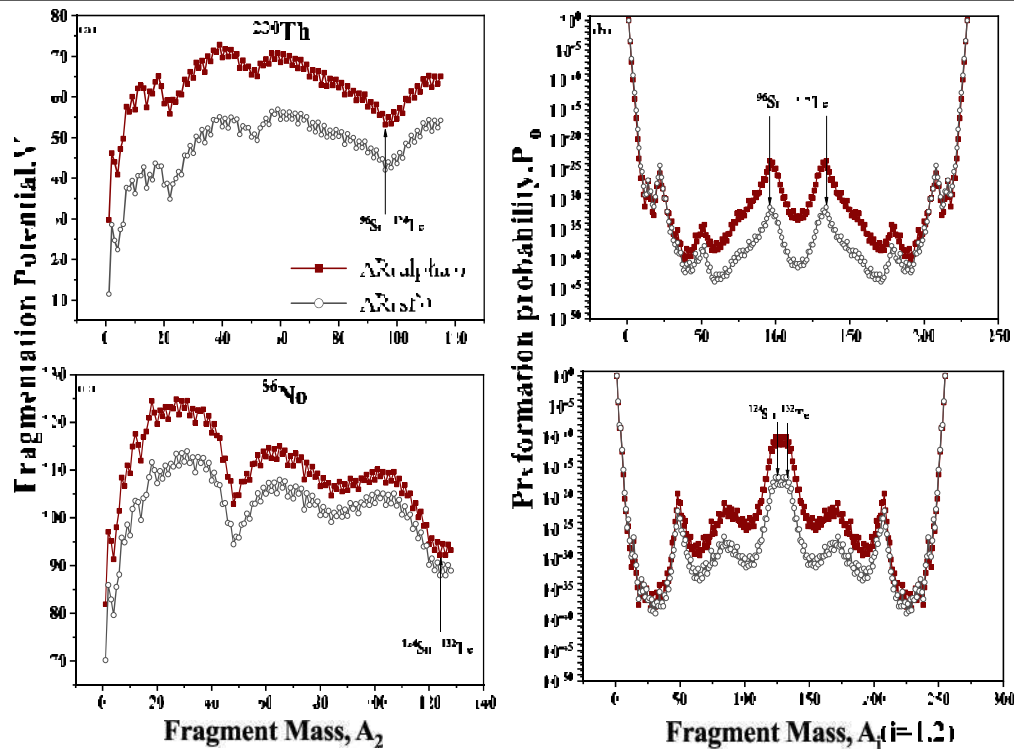


Figure 3.7: Fragmentation potential and Preformation probability of nuclei for (a),(b) ^{230}Th and (c),(d) ^{256}No for alpha and spontaneous fission by taking emitting fragments as spheres only.

structure and P_0 is made for ^{230}Th and ^{256}No nuclei (extreme nuclei of the chosen mass region). The trend of the fragmentation structure for ^{230}Th and ^{256}No nuclei (see Fig. 3.7(a) and (c)) remains the similar for both modes (α and SF), but change in the magnitude of the fragmentation potential is observed. The minima in the fragmentation potential suggests the most probable decay fragments. The identified fission fragments using the minima of the fragmentation potential for alpha decay and SF for ^{230}Th and ^{256}No nuclei are $^{96}\text{Sr}+^{134}\text{Te}$ and $^{124}\text{Sn}+^{132}\text{Te}$ respectively. After the fragmentation structure, the preformation probability is calculated and plotted with respect to fragment mass A_i and shown in Fig. 3.7(b) and (d). The trend of the preformation probability is also similar for ^{230}Th and ^{256}No nuclei for α and SF decay modes. It may be noted that the fission characteristics evolve from an asymmetric mode to a predominantly symmetric mode as one moves from ^{230}Th to ^{256}No nucleus. It would be of considerable interest to investigate the specific transition point at which the fission mass distribution shifts from an asymmetric to a symmetric mode

To get a better insight of this transition, we have taken two more isotopes (^{252}Cf and ^{256}Fm) from the chosen range of the nuclei and P_0 is plotted with respect to A_i ($i=1,2$)

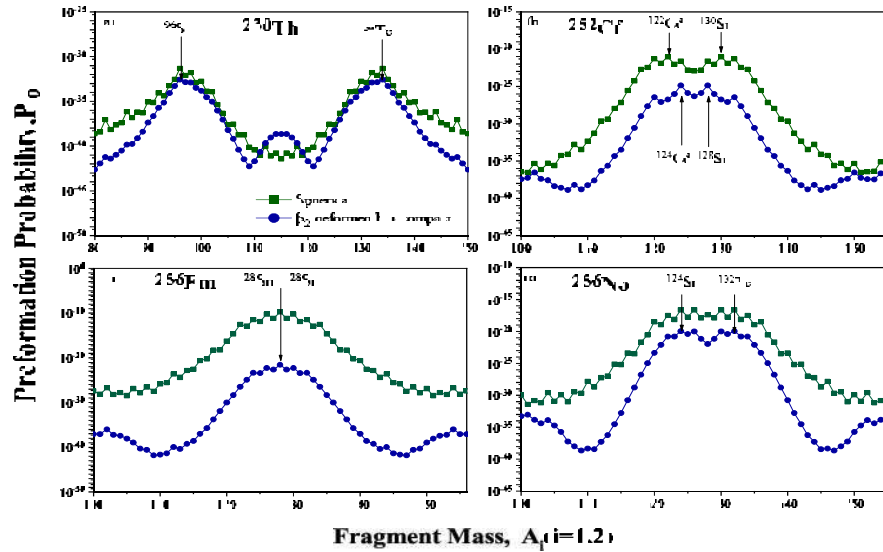


Figure 3.8: The preformation yield P_0 is plotted as a function of fission fragments (a) ^{230}Th , (b) ^{252}Cf , (c) ^{256}Fm and (d) ^{256}No for spherical fragments as well as β_2 deformed hot compact configurations.

and shown in Fig. 3.8. For the spontaneous fission analysis, the $\log T_{1/2}$ is calculated for ^{230}Th , ^{252}Cf , ^{256}Fm and ^{256}No nuclei firstly for the spherical case. In the next step, deformation effects (β_2) are incorporated, together with the hot optimum orientations of the decay fragments. The comparison between the calculated $\log T_{1/2}$ and the experimental values [?] is presented in Table 3.6. Overall, the calculated half-lives exhibit satisfactory agreement with the measured data, except in the case of the spherical configuration of the fragments for the ^{256}Fm nucleus, where the theoretical estimates underestimate the experimentally observed SF half-life. It is relevant to note that the half-life increases with decrease in ΔR value. But in the case of ^{256}Fm the ΔR cannot be reduced further as $V(R_a)$ becomes less than the Q_{sf} (Q-value of the decaying channel). On the other hand we have reasonable scope of ΔR extension for ^{256}No because barrier characteristics got modified as Coulomb repulsion increases with increase in atomic number. Interestingly, barrier height can be altered for ^{256}Fm nucleus by adding deformations. The calculated half life of ^{256}Fm got modified by taking hot-compact choice of fragments as shown in Table 3.6.

The most probable fragments for spherical as well as a hot-compact configuration are also shown in Table 3.6. For ^{230}Th nucleus, the asymmetric fission fragments $^{96}\text{Sr} + ^{134}\text{Te}$ ($N=82$)

Table 3.6: The PCM-calculated SF half-lives together with fitted neck-length parameter ΔR are presented. The choice of outgoing fragment is based on most probable fragment identified through highest P_o value. For each nucleus, both spherical and β_2 -deformed (hot) orientations are considered. The calculated half-lives further compared with available data [?].

Parent nucleus	Decay channel	R_a (fm)	$\log_{10} T_{1/2}^{SF}(\text{sec})$ (PCM)	$\log_{10} T_{1/2}^{SF}(\text{sec})$ (Exp.)
Spherical				
^{230}Th	$^{96}\text{Sr}+^{134}\text{Te}$	10.82	24.25	24.79
^{252}Cf	$^{122}\text{Cd}+^{130}\text{Sn}$	11.33	9.00	9.43
^{256}Fm	$^{128}\text{Sn}+^{128}\text{Sn}$	12.20	-7.36	4.01
^{256}No	$^{124}\text{Sn}+^{132}\text{Te}$	11.49	2.31	2.73
Deformed				
^{230}Th	$^{96}\text{Sr}+^{134}\text{Te}$	11.34	24.16	24.79
^{252}Cf	$^{124}\text{Cd}+^{128}\text{Sn}$	12.12	9.40	9.43
^{256}Fm	$^{128}\text{Sn}+^{128}\text{Sn}$	12.24	4.25	4.01
^{256}No	$^{124}\text{Sn}+^{132}\text{Te}$	12.37	2.09	2.73

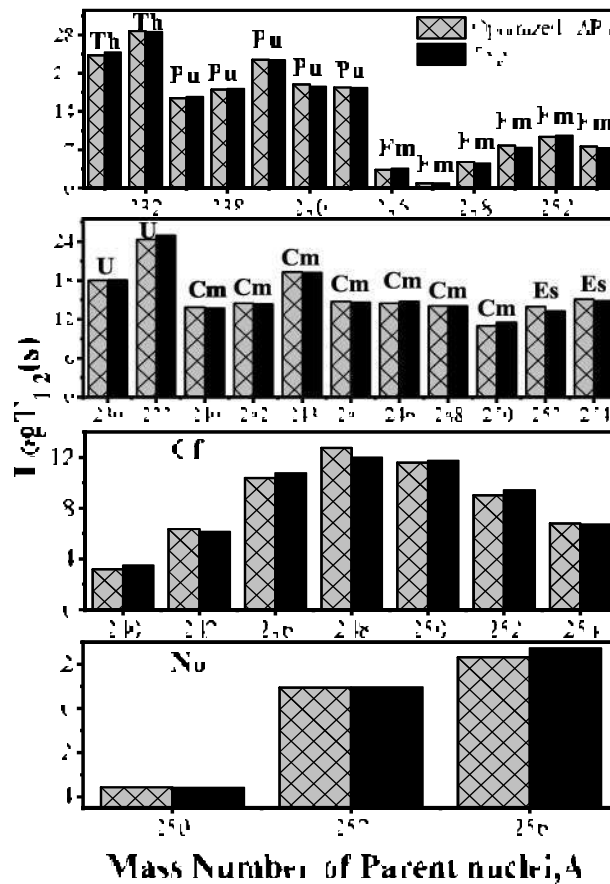


Figure 3.9: Logarithmic of half-lives for 34 nuclei undergoing spontaneous fission ranging Z from 89-102 compared with experimental half-lives by optimizing ΔR .

are identified, which lie nearby $N=82$ and deformed magic number $Z=38$. For the ^{252}Cf nucleus, asymmetric fragments ($^{122}\text{Cd}+^{130}\text{Sn}$) are identified, that lie nearby $Z=50$. The symmetric fission fragments of ^{256}Fm also belong to spherical magic shell closure $\text{Sn}(Z=50)$ and near neutron shell closure $N=82$. Similarly, symmetric fragments of ^{256}No are identified nearby $Z=50$. This indicates that the proton and neutron shell closure play an important role in the SF region. These results show a fair agreement with ref.[? ?]. Further, the half-life of SF is calculated for chosen set of nuclei $Z\sim 89-102$, whose experimental data is available. For these cases neck length parameter (ΔR) ranges from -0.5 to 0.8 fm. The comparison between calculated half-life and experimental data is shown in Fig. 3.9. The calculated results show a good agreement with experimental data [? ? ?].

In addition to this, TKE is also studied for these nuclei as TKE plays crucial role in SF dynamics. It alter its behaviour with respect to symmetry/asymmetry of the decaying fragments.

It can be computed by using relation [?] as follows:

$$TKE = \frac{0.2904(Z_1 + Z_2)^2}{A_1^{1/3} + A_2^{1/3} - (A_1 + A_2)^{1/3}} \frac{A_1 A_2}{(A_1 + A_2)^2} \quad (3.7)$$

where A_1 and A_2 are the mass numbers of emitted fragments respectively. Firstly, TKE is calculated for those nuclei whose experimental data is available and is shown in Table 3.7. In view of the fact that fragments appearing at minima in Eq. (2.3) correspond to the most probable fragments, it is observed that the calculated results find in good agreement with experimental data. Secondly, there are nuclei whose experimental analysis is not available for spontaneous fission. Therefore, an attempt is made to predict TKE for cases where experimental data is absent and shown in Fig. 3.10. It is evident from this figure that the TKE of the fragments exhibits a clear increasing trend with the rise in the fissility parameter ($Z^2/A^{1/3}$). Because of an increase in the fissile nature of the nuclei, the mass of the decaying fragments increases, leading to an increase in the TKE values. Additionally, a systematic comparison of the calculated TKE values with the corresponding experimental measurements would constitute an important avenue for future study. In the next section, investigation of α and 2α emission is studied in detail.

Table 3.7: The calculated total kinetic energy (TKE) of fission fragments and corresponding experimental data [? ? ?] are listed.

Parent nucleus	Decay channel	TKE(MeV)	
		Calc.	Expt.
^{238}Pu	$^{104}\text{Mo} + ^{134}\text{Te}$	174.26	177.00 ± 0.5
^{240}Pu	$^{106}\text{Mo} + ^{134}\text{Te}$	174.05	179.40 ± 0.5
^{242}Pu	$^{110}\text{Ru} + ^{132}\text{Sn}$	174.23	180.70 ± 0.5
^{246}Cm	$^{116}\text{Pd} + ^{130}\text{Sn}$	181.37	183.90 ± 1.0
^{248}Cm	$^{116}\text{Pd} + ^{132}\text{Sn}$	180.77	182.20 ± 0.9 , 179.00 ± 2.0
^{248}Cf	$^{120}\text{Cd} + ^{128}\text{Sn}$	188.79	188.70 ± 1.3
^{250}Cf	$^{120}\text{Cd} + ^{130}\text{Sn}$	188.21	187.00 ± 1.0 , 185.00 ± 3.0
^{252}Cf	$^{122}\text{Cd} + ^{130}\text{Sn}$	187.79	185.9 ± 1.0 , 185.70 ± 0.1 , 183.00 ± 0.5
^{254}Cf	$^{122}\text{Cd} + ^{132}\text{Sn}$	187.20	186.90 ± 1.0 , 185.00 ± 2.0
^{253}Es	$^{125}\text{In} + ^{128}\text{Sn}$	191.50	188.00 ± 3.0
^{254}Fm	$^{126}\text{Sn} + ^{128}\text{Sn}$	195.15	195.1 ± 1.0 , 189.00 ± 2.0
^{256}Fm	$^{126}\text{Sn} + ^{130}\text{Sn}$	194.65	197.9 ± 1.0
^{252}No	$^{122}\text{Sn} + ^{130}\text{Sn}$	203.43	202.4 ± 0.0 , 194.30 ± 3.0

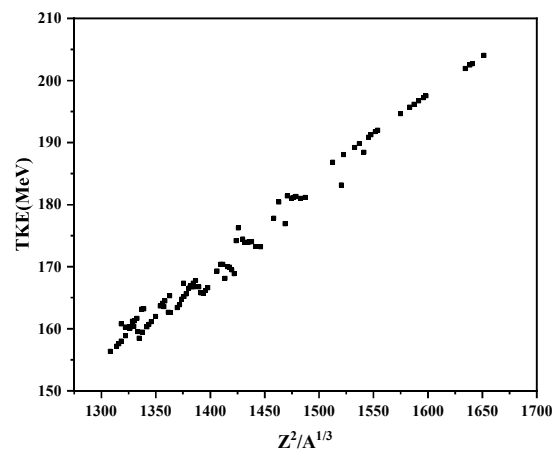


Figure 3.10: TKE vs $Z^2/A^{1/3}$ for 93 nuclei ranging Z=89-102.

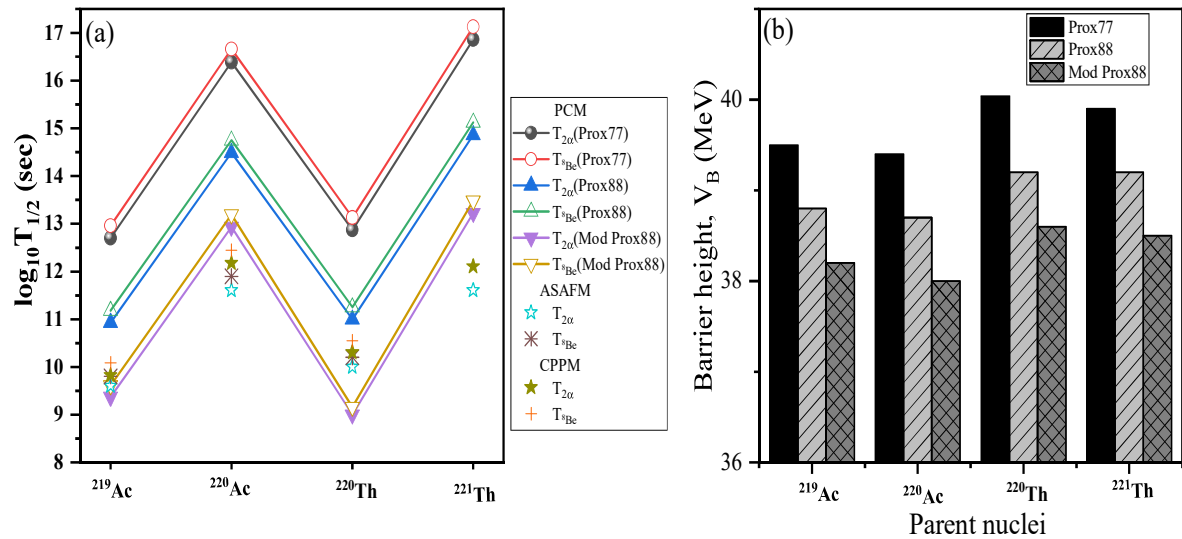


Figure 3.11: (a) Calculated half-lives ($\log_{10} T_{1/2}$ in seconds) for the decay of ^8Be and simultaneous 2α decay of parent nuclei ^{219}Ac , ^{220}Ac , ^{220}Th , and ^{221}Th , comparing three proximity potentials: Prox 77, Prox 88, and Modified Prox 88. (b) Corresponding barrier height (V_B) for 2α emission as a function of the parent nucleus.

3.3 Discussion-II

Calculations and Results

First of all, the analysis begin within the PCM methodology to investigate the competition between ^8Be emission and the simultaneous emission of two alpha particles (2α decay). Since the probability of decay strongly depends on the barrier characteristics, careful attention is given to the choice of the nuclear interaction potential. The nuclear potential plays a crucial role in determining the barrier height, width, and overall shape, which directly influence the cluster preformation probability, barrier penetrability, and consequently, the half-life of the decay process. In view of this, three different nuclear potentials are considered: Proximity 77, Proximity 88, and Modified Proximity 88. The systems $^{219,220}\text{Ac}$ and $^{220,221}\text{Th}$ are selected for this study, as these nuclei lie in a region where both 2α and ^8Be decay modes are energetically allowed and have been previously investigated using theoretical models like the Analytical Super-Asymmetric Fission Model (ASAFM) [?] and the Coulomb and Proximity Potential Model (CPPM) [?]. Figure 3.11(a) presents the calculated logarithm of half-lives ($\log_{10} T_{1/2}$, in seconds) for the 2α and ^8Be

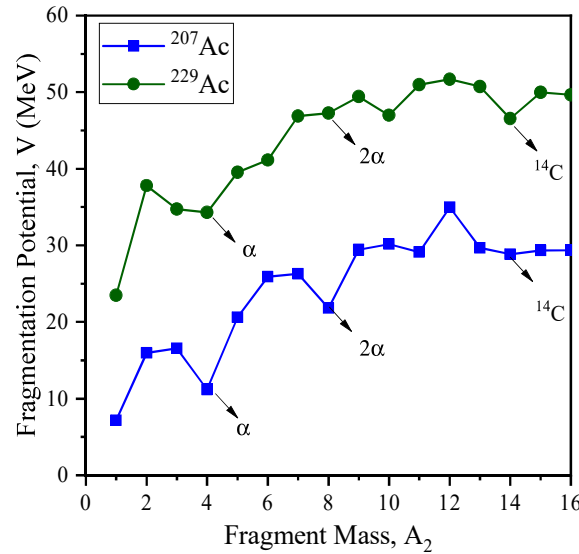


Figure 3.12: (a) Fragmentation potential $V(\eta)$ versus fragment mass number A_2 for the lightest (^{207}Ac) and heaviest (^{229}Ac) actinium isotopes.

emission modes. The results obtained using PCM with different proximity potentials are compared alongside predictions from ASAFM and CPPM. It is observed that the Modified Prox 88 potential gives consistently lower half-lives for both decay modes, indicating a reduced barrier and enhanced penetrability. Among the three potentials, the results with Modified Prox 88 are found to be in closest agreement with earlier theoretical results [?], suggesting its suitability for studying 2α and cluster emissions. To provide a quantitative measure, we have calculated the root-mean-square (RMS) deviations of $\log_{10} T_{1/2}$ values for the nuclei shown in Fig. 3.11. We have compared our PCM results with established models like ASAFM [?] and CPPM [?] calculations. The results, summarized in Table 3.8, show that Modified Prox. 88 yields the smallest RMS deviations and is therefore adopted for the subsequent calculations.

Table 3.8: Comparison of RMS values for ASAFM and CPPM using different proximity potentials.

	ASAFM (RMS)			CPPM (RMS)		
	Prox77	Prox88	Mod Prox88	Prox77	Prox88	Mod Prox88
2α	4.77	1.72	1.34	4.29	2.21	1.11
^8Be	4.54	2.35	1.17	4.04	1.86	1.16

Since the decay half-lives are directly influenced by the barrier characteristics, Figure 3.11(b) displays the corresponding barrier heights (V_B) calculated for all four systems

Table 3.9: The PCM-calculated results for actinium isotopes. For each parent nucleus ^AAc (mass number A), the table lists the α and 2α decay Q -values (in MeV), the optimized neck-length parameter ΔR (in fm), and the calculated $\log_{10} T_{1/2}$ (in seconds) using the PCM with the Modified Prox 88 potential. Wherever available, the calculated $\log_{10} T_{1/2}$ values are compared with experimental data [?] as well as other theoretical predictions [? ?]. The ΔR parameters are chosen to reproduce the known α -decay half-lives, providing a consistent basis for predicting the rarer 2α decay channels.

Parent nucleus	Decay channel	Q-Value (MeV)	PCM		Half-life($\log_{10} T_{1/2}(\text{sec})$)		
			ΔR	$\log_{10} T_{1/2}(\text{sec})$	[?]	CPPM[?]	ASAFM[?]
^{207}Ac	$^{203}\text{Fr} + ^4\text{He}$	7.85	1.21	-2.35	-1.66		
	$^{199}\text{At} + 2\alpha$	15.12	1.12	15.04			
^{208}Ac	$^{204}\text{Fr} + ^4\text{He}$	7.71	1.22	-0.90	-1.02		
	$^{200}\text{At} + 2\alpha$	14.49	1.13	17.53			
^{209}Ac	$^{205}\text{Fr} + ^4\text{He}$	7.72	1.20	-1.37	-1.00		
	$^{201}\text{At} + 2\alpha$	14.78	1.11	16.68		1.24	
^{210}Ac	$^{206}\text{Fr} + ^4\text{He}$	7.60	1.22	-0.36	-0.44		
	$^{202}\text{At} + 2\alpha$	14.53	1.13	19.18		6.78	
^{211}Ac	$^{207}\text{Fr} + ^4\text{He}$	7.62	1.20	-1.05	-0.60		
	$^{203}\text{At} + 2\alpha$	14.51	1.11	18.28		3.56	
^{212}Ac	$^{208}\text{Fr} + ^4\text{He}$	7.52	1.22	-0.11	-0.02		
	$^{204}\text{At} + 2\alpha$	14.30	1.13	20.55			
^{213}Ac	$^{209}\text{Fr} + ^4\text{He}$	7.50	1.19	-0.09	-0.10		
	$^{205}\text{At} + 2\alpha$	14.27	1.10	19.51			
^{214}Ac	$^{210}\text{Fr} + ^4\text{He}$	7.35	1.20	1.05	0.01		
	$^{206}\text{At} + 2\alpha$	14.02	1.11	21.74			
^{215}Ac	$^{211}\text{Fr} + ^4\text{He}$	7.74	1.21	-0.72	-0.77		
	$^{207}\text{At} + 2\alpha$	14.41	1.12	20.30			
^{216}Ac	$^{212}\text{Fr} + ^4\text{He}$	9.23	1.38	-4.71	-5.60		
	$^{208}\text{At} + 2\alpha$	15.76	1.27	18.48			
^{217}Ac	$^{213}\text{Fr} + ^4\text{He}$	9.83	1.35	-7.27	-7.16		
	$^{209}\text{At} + 2\alpha$	16.73	1.25	17.73		14.78	
^{218}Ac	$^{214}\text{Fr} + ^4\text{He}$	9.37	1.38	-5.07	-5.96		
	$^{210}\text{At} + 2\alpha$	17.96	1.27	11.85		11.17	
^{219}Ac	$^{215}\text{Fr} + ^4\text{He}$	8.82	1.30	-4.19	-4.92		
	$^{211}\text{At} + 2\alpha$	18.27	1.20	9.61		9.82	9.6
^{220}Ac	$^{216}\text{Fr} + ^4\text{He}$	8.34	1.29	-1.60	-3.28		
	$^{212}\text{At} + 2\alpha$	17.52	1.19	12.91		12.17	11.6
^{221}Ac	$^{217}\text{Fr} + ^4\text{He}$	7.78	1.20	0.32	-1.58		
	$^{213}\text{At} + 2\alpha$	16.25	1.11	15.32		16.12	
^{222}Ac	$^{218}\text{Fr} + ^4\text{He}$	7.13	1.38	0.83	0.73		
	$^{214}\text{At} + 2\alpha$	15.15	1.27	20.97			

Table 3.9 continued...

Parent nucleus	Decay channel	Q-Value (MeV)	PCM		Half-life($\log_{10}T_{1/2}(\text{sec})$)		
			ΔR	$\log_{10}T_{1/2}(\text{sec})$	[?]	CPPM[?]	ASAFM[?]
^{223}Ac	$^{219}\text{Fr} + ^4\text{He}$	6.78	1.24	2.10	2.00		
	$^{215}\text{At} + 2\alpha$	14.23	1.15	22.57			
^{224}Ac	$^{220}\text{Fr} + ^4\text{He}$	6.32	1.26	4.50	3.91		
	$^{216}\text{At} + 2\alpha$	13.12	1.16	27.65			
^{225}Ac	$^{221}\text{Fr} + ^4\text{He}$	5.93	1.22	5.62	5.74		
	$^{217}\text{At} + 2\alpha$	12.39	1.13	29.69			
^{226}Ac	$^{222}\text{Fr} + ^4\text{He}$	5.50	1.26	8.30	7.81		
	$^{218}\text{At} + 2\alpha$	11.36	1.16	35.89			
^{227}Ac	$^{223}\text{Fr} + ^4\text{He}$	5.04	1.20	10.07	10.71		
	$^{219}\text{At} + 2\alpha$	10.60	1.11	38.47			
^{228}Ac	$^{224}\text{Fr} + ^4\text{He}$	4.72	1.20	12.69	12.13		
	$^{220}\text{At} + 2\alpha$	9.67	1.11	45.43			
^{229}Ac	$^{225}\text{Fr} + ^4\text{He}$	4.44	1.20	13.73	15.28		
	$^{221}\text{At} + 2\alpha$	9.05	1.11	48.43			

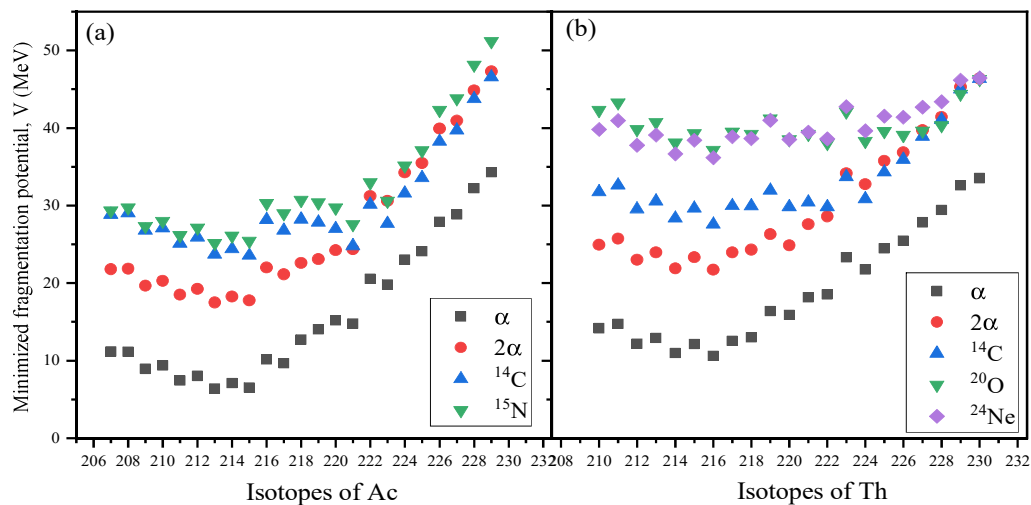


Figure 3.13: The minimized potentials for α , 2α , ^{14}C , ^{15}N , ^{20}O , and ^{24}Ne emissions are plotted across a range of (a) Ac isotopes and (b) Th isotopes.

Table 3.10: Same as Table II, but for thorium (^{A}Th) isotopes. The listed quantities include the Q -values (in MeV) for α and 2α decays, the optimized neck-length parameter ΔR (in fm), and the calculated $\log_{10} T_{1/2}$ (in seconds) using the PCM with the Modified Prox 88 potential. The ΔR values are fitted to known α -decay half-lives and subsequently used to predict the corresponding 2α decay properties. The results are compared with experimental data and other theoretical estimates where available.

Parent nucleus	Decay channel	Q-Value (MeV)	PCM		Half-life($\log_{10} T_{1/2}(\text{sec})$)		
			ΔR	$\log_{10} T_{1/2}(\text{sec})$	[?]	CPPM[?]	ASAFM[?]
^{210}Th	$^{206}\text{Ra} + ^4\text{He}$	8.06	1.21	-2.613	-2.05		
	$^{202}\text{Rn} + 2\alpha$	15.48	1.12	15.13			
^{211}Th	$^{207}\text{Ra} + ^4\text{He}$	7.94	1.24	-1.55	-1.52		
	$^{203}\text{Rn} + 2\alpha$	15.21	1.00	18.11		-0.181	
^{212}Th	$^{208}\text{Ra} + ^4\text{He}$	7.95	1.2	-1.642	-1.52		
	$^{204}\text{Rn} + 2\alpha$	15.23	1.11	16.33			
^{213}Th	$^{209}\text{Ra} + ^4\text{He}$	7.83	1.23	-0.939	-0.85		
	$^{205}\text{Rn} + 2\alpha$	14.98	1.14	18.92			
^{214}Th	$^{210}\text{Ra} + ^4\text{He}$	7.82	1.20	-1.195	-1.00		
	$^{206}\text{Rn} + 2\alpha$	14.98	1.11	17.60			
^{215}Th	$^{211}\text{Ra} + ^4\text{He}$	7.66	1.24	-0.608	-0.68		
	$^{207}\text{Rn} + 2\alpha$	14.70	1.14	20.14			
^{216}Th	$^{212}\text{Ra} + ^4\text{He}$	8.07	1.21	-1.343	-1.55		
	$^{208}\text{Rn} + 2\alpha$	15.10	1.12	18.07			
^{217}Th	$^{213}\text{Ra} + ^4\text{He}$	9.43	1.28	-3.60	-3.60		
	$^{209}\text{Rn} + 2\alpha$	16.29	1.18	16.46			
^{218}Th	$^{214}\text{Ra} + ^4\text{He}$	9.85	1.32	-6.847	-6.96		
	$^{210}\text{Rn} + 2\alpha$	17.12	1.22	12.84		14.44	
^{219}Th	$^{215}\text{Ra} + ^4\text{He}$	9.51	1.38	-5.36	-5.96		
	$^{211}\text{Rn} + 2\alpha$	18.37	1.27	11.13		10.88	
^{220}Th	$^{216}\text{Ra} + ^4\text{He}$	8.95	1.30	-4.889	-5.01		
	$^{212}\text{Rn} + 2\alpha$	18.48	1.20	8.92		10.489	10.0
^{221}Th	$^{217}\text{Ra} + ^4\text{He}$	8.62	1.29	-2.078	-2.77		
	$^{213}\text{Rn} + 2\alpha$	17.78	1.19	13.21		12.40	11.6
^{222}Th	$^{218}\text{Ra} + ^4\text{He}$	8.12	1.27	-2.505	-2.55		
	$^{214}\text{Rn} + 2\alpha$	16.67	1.17	14.71		15.65	
^{223}Th	$^{219}\text{Ra} + ^4\text{He}$	7.56	1.40	-0.203	-0.22		
	$^{215}\text{Rn} + 2\alpha$	15.70	1.29	20.14			

Table 3.10 continued...

Parent nucleus	Decay channel	Q-Value (MeV)	PCM		Half-life($\log_{10}T_{1/2}(\text{sec})$)		
			ΔR	$\log_{10}T_{1/2}(\text{sec})$	[?]	CPPM[?]	ASAFM[?]
^{224}Th	$^{220}\text{Ra} + ^4\text{He}$	7.30	1.25	0.166	0.11		
	$^{216}\text{Rn} + 2\alpha$	14.89	1.15	20.81			
^{225}Th	$^{221}\text{Ra} + ^4\text{He}$	8.62	1.25	2.86	2.72		
	$^{217}\text{Rn} + 2\alpha$	13.80	1.15	25.61			
^{226}Th	$^{222}\text{Ra} + ^4\text{He}$	6.45	1.23	3.45	3.38		
	$^{218}\text{Rn} + 2\alpha$	13.13	1.14	26.90			
^{227}Th	$^{223}\text{Ra} + ^4\text{He}$	6.14	1.20	6.32	6.21		
	$^{219}\text{Rn} + 2\alpha$	12.12	1.11	32.50			
^{228}Th	$^{224}\text{Ra} + ^4\text{He}$	5.52	1.20	7.578	7.92		
	$^{220}\text{Rn} + 2\alpha$	11.31	1.11	34.99			
^{229}Th	$^{225}\text{Ra} + ^4\text{He}$	5.16	1.20	10.62	10.44		
	$^{221}\text{Rn} + 2\alpha$	10.26	1.11	42.62			
^{230}Th	$^{225}\text{Ra} + ^4\text{He}$	4.77	1.16	12.09	12.49		
	$^{222}\text{Rn} + 2\alpha$	9.62	1.07	44.96			

using the three proximity potentials. As expected, different potentials yield distinct barrier heights. A systematic reduction in the barrier height is observed when moving from Prox 77 to Prox 88, and further to Modified Prox 88. The lower barrier height obtained with the Modified Prox 88 potential correlates well with the reduced half-lives seen in Figure 3.11(a), confirming that a smaller barrier facilitates higher cluster penetrability and the shorter decay times. This initial comparative study underscores the importance of the selection of nuclear potential in reference to appropriate modeling of 2α and ^8Be decay modes. Based on these findings, further calculations are carried out for a wider range of actinium and thorium isotopes using the Modified Proximity 88 potential.

Next, to investigate the decay dynamics across a broader range of isotopes, we aim to analyze the potential landscape experienced by the emitted fragments. Building upon this, we have addressed the α -decay half-lives for all Ac and Th isotopes for which experimental data is available, using the Modified Proximity 88 potential. The neck-length parameters (ΔR) are optimized to reproduce the experimental data [?] wherever available, and theoretical predictions are employed otherwise. The ΔR values for both Ac and Th isotopes, along with the corresponding Q -values and half-lives, are listed in Table 3.9 and Table 3.10, where a comparison with available data [? ? ?] is also provided. At these neck-length values, we further explore the decay systematics and the competition

between two-alpha (2α) and heavier cluster emissions through the fragmentation potential analyses, presented in Figures 3.12 and 3.13.

Note that within the PCM framework, the minimized fragmentation potential represents the energy minimum of the decaying fragments, and plays a crucial role in determining the cluster preformation probability and, subsequently, the decay half-life. Figure 3.12 illustrates the calculated fragmentation potential for two extreme cases of Ac isotopes, namely ^{207}Ac and ^{229}Ac . One can clearly see that α decay appears as the most probable decay mode as evidenced by the deepest potential minimum. For the lighter isotope ^{207}Ac , the minimized potential for 2α emission is lower than that for ^{14}C , indicating a preference for two-alpha decay. However, moving towards heavier isotopes like ^{229}Ac , the ^{14}C cluster becomes increasingly competitive, suggesting a gradual shift in decay preference with increasing mass number or N/Z ratio. A similar analysis for Th isotopes (not shown here to avoid repetition) reveals that while 2α emission is favored in lighter isotopes, the potential minima for ^{14}C emission becomes more prominent in the heavier ^{230}Th isotope.

It is important to note that although clusters such as ^{15}N , ^{20}O , and ^{24}Ne have been experimentally observed [? ?] in heavier isotopes of Ac and Th, we restrict our heavier-cluster comparison primarily to ^{14}C . This choice is motivated by three considerations: (i) ^{14}C emission is consistently observed [? ?] across both Ac and Th isotopes, enabling uniform comparisons with α and 2α emissions; (ii) for cases where multiple clusters are emitted from the same parent, such as ^{223}Ac , ^{14}C decay exhibits shorter half-lives compared to ^{15}N [? ?], making it comparatively more probable; and (iii) since our aim is to examine the competition between α , 2α , and one representative heavier cluster, ^{14}C is the most suitable choice as it is the lightest among the observed clusters and provides a consistent benchmark. Figure 3.13 extends our analysis to include other experimentally observed clusters, namely ^{15}N , ^{20}O , and ^{24}Ne , in addition to α , 2α , and ^{14}C . In Fig. 3.13(a), the results are shown across a range of Ac isotopes, while Fig. 3.13(b) corresponds to selected Th isotopes. For both Ac and Th nuclei, 2α emission is energetically favored in the lighter mass region, whereas, with increasing neutron number, heavier clusters such as ^{14}C , ^{15}N , ^{20}O , and ^{24}Ne gradually become more competitive. Among these heavier clusters, ^{14}C generally exhibits the lowest minimized potential across a wider isotopic range, making it

the most probable heavier-cluster decay mode. While lighter isotopes favor 2α emission, heavier clusters begin to play a more significant role as the mass number increases. Thus, the combined analysis of Figures 3.12 and 3.13 clearly demonstrates the systematic shift in decay preference from dominant two-alpha emission in lighter isotopes to heavier cluster decay modes in isotopes with higher mass number or N/Z ratio. This behavior reflects structural changes in the nuclear potential landscape with increasing neutron number. It further highlights the predictive strength of PCM when guided by carefully chosen interaction potentials and fitted parameters. These results are further validated by the fact that experimental cluster emissions have predominantly been observed [? ?] in heavier isotopes of Ac and Th, thereby justifying the theoretical findings presented in this present work. Following the above investigations, it becomes essential to advance the understanding of 2α decay systematics. In this context, Figure 3.14 presents the behavior of the interaction potential and neck-length parameter (ΔR) associated with both α and 2α decay channels, using the PCM. Figure 3.14(a) displays the scattering potential for the decay of ^{219}Ac as a function of the inter-nuclear separation R . This potential is obtained by normalizing the fragmentation potential with respect to the binding energy and represents the energy path along which the preformed cluster tunnels through the interaction barrier. The potential profile clearly indicate that the barrier height (V_B) is higher for 2α emission than for single α decay. A higher barrier implies lower penetrability, and therefore, a longer half-life for 2α emission. The locations of the first turning points (R_a) for both decay modes are also marked in the figure. Importantly, R_a depends directly on the neck-length parameter ΔR . The parameter ΔR signifies the effective separation at which the cluster is assumed to be preformed within the parent nucleus. It encapsulates the effects of overlapping density distributions and collective deformations, and plays a critical role in identifying the barrier region for the WKB tunneling calculation.

To establish a consistent framework for predicting 2α decay half-lives, Figure 3.14(b) analyzes the variation of ΔR values for four benchmark systems: $^{219,220}\text{Ac}$ and $^{220,221}\text{Th}$. The ΔR values are derived in reference to experimental α decay half-lives [?] and are compared with those used in 2α decay calculations. It is observed that the ΔR values for 2α decay are consistently smaller than those for single α emission. This trend

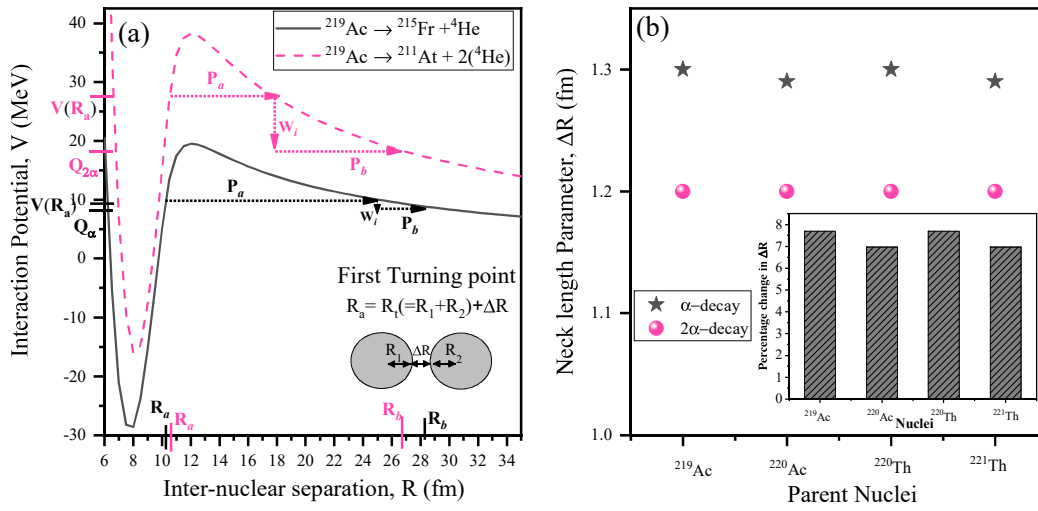


Figure 3.14: (a) Interaction potential $V(R)$ in the PCM for ^{219}Ac decaying via α (to ^{215}Fr) and simultaneous 2α (to ^{211}At), plotted as a function of the inter-nuclear separation R . (b) Optimized neck-length parameter ΔR (in fm) for each parent nucleus (Ac and Th) used in the PCM fits. The inset displays the percentage difference in ΔR between the α and 2α decay modes across isotopes.

can be understood by examining the nuclear dynamics that govern the two processes. While ΔR is often linked to the decay time scale, it also defines the starting point for barrier penetration and characterizes the spatial region where the cluster is assumed to be preformed within the parent nucleus. In the case of 2α decay, the emitted particles are treated as a bound cluster. This composite system experiences a stronger Coulomb repulsion than a single α particle, leading to a higher potential barrier and a longer decay half-life for 2α emission.

To quantify this trend, the inset of Figure 3.14(b) displays the percentage difference between the fitted ΔR values for α and 2α decay, defined as:

$$\text{Percentage Difference} = \left(\frac{\Delta R_{\alpha} - \Delta R_{2\alpha}}{\Delta R_{\alpha}} \right) \times 100\% \quad (3.8)$$

The calculated differences for the four systems yield an average reduction of approximately 7.3% in ΔR for 2α decay. This average correction is then applied across the full set of Ac and Th isotopes, by reducing the α decay neck-length values by 7.3% to obtain the corresponding ΔR for 2α decay. These neck length values are subsequently used to calculate the 2α decay half-lives within the PCM framework. Note that the systematic reduction of the ΔR by $\sim 7.3\%$ for the 2α case arises from the combined effects of increased

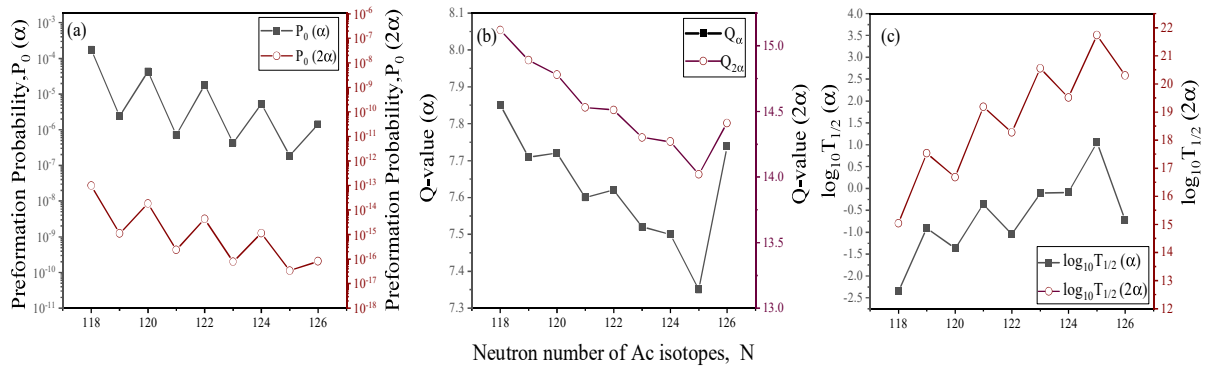


Figure 3.15: Odd-even staggering (OES) in actinium isotopes: Shown are (a) the α preformation probability P_0 , (b) decay Q -value, and (c) $\log_{10} T_{1/2}$ (s) as functions of neutron number N for Ac isotopes, comparing α (solid symbols) and 2α (open symbols) decay channels.

Coulomb repulsion and the modified geometry of the two- α composite system compared to a single α particle. While the α particle is compact and spherical ($Z=2$), the two- α composite carries a higher charge ($Z=4$) and exhibits a more extended spatial configuration. This enhanced Coulomb repulsion shifts the barrier outward and alters the inner turning point of the potential, thereby influencing the penetrability. As shown in Fig. 3.14 (a), the potential barrier for 2α emission is significantly higher than that for single α emission, illustrating this difference in barrier characteristics. The resulting predictions, obtained using PCM with the Modified Prox 88 potential, are summarized in Tables 3.9 and 3.10 for isotopes ranging from $A = 207$ to 229 in actinium and $A = 210$ to 230 in thorium. In addition to half-lives, the tables also include the corresponding Q -values and ΔR values used in the calculations. The predicted results are compared with theoretical values reported from the ASAFM [?] and CCPM approaches [?], wherever available. Note that we have opted for unique difference in the neck-length for α and 2α emissions so as to make possible predictions of 2α decay modes, including cases where no prior model estimates are available. This treatment introduces minor deviations in some of the α -decay half-lives, leading to differences of about one to two orders of magnitude in $\log_{10} T_{1/2}$ for a few cases reported in Table 3.9 and Table 3.10. To quantify this, we have calculated the root-mean-square (RMS) deviation of the PCM calculated α -decay half-lives relative to experimental values for all Ac and Th isotopes listed in Table 3.9 and Table 3.10. The

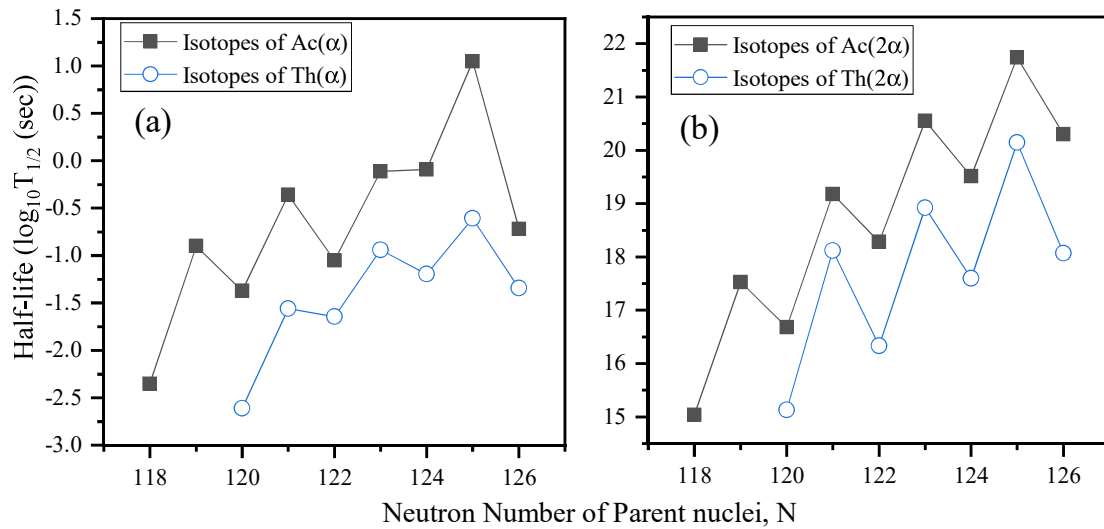


Figure 3.16: Variation of calculated half-lives for α and 2α emissions in Ac and Th isotopes as a function of neutron number. Panel (a) displays the results for α decay, while panel (b) shows the corresponding values for 2α emission.

resulting RMS deviation is 0.80 for Ac and 0.28 for Th isotopes, which lies well within acceptable limits, thereby validating the reliability of the present calculations.

To gain deeper insight into the underlying nuclear structure effects influencing decay behavior, Figures 3.15 and 3.16 examine the presence of odd-even staggering (OES) in actinium and thorium isotopes with neutron numbers $N \leq 126$. This region of relatively lighter isotopes is particularly sensitive to pairing correlations, making it well-suited for investigating OES signatures within the Preformed Cluster-decay Model (PCM). The motivation to probe such effects arises from the structure of the minimized potential shown in Figure 3.11, where alternating depth patterns suggest enhanced preformation for both α and 2α clusters in even- N isotopes. Since the fragmentation potential reflects the behavior of formation probability of various decay fragments, its staggering behavior naturally motivates a detailed analysis of preformation probabilities (P_0), Q -value, and logarithmic half-life ($\log_{10} T_{1/2}$) across the isotopes of interest.

In view of this, Figure 3.15 analyzes these observables for Ac isotopes. A pronounced odd-even pattern is evident, especially in P_0 and $\log_{10} T_{1/2}$. As shown in Figures 3.15(a) and 3.15(c), odd- N isotopes consistently exhibit lower preformation probabilities, leading to longer half-lives compared to their even- N counterparts. This suppression is attributed to the unpaired neutron in odd- N nuclei, which inhibits the formation of a well-defined α

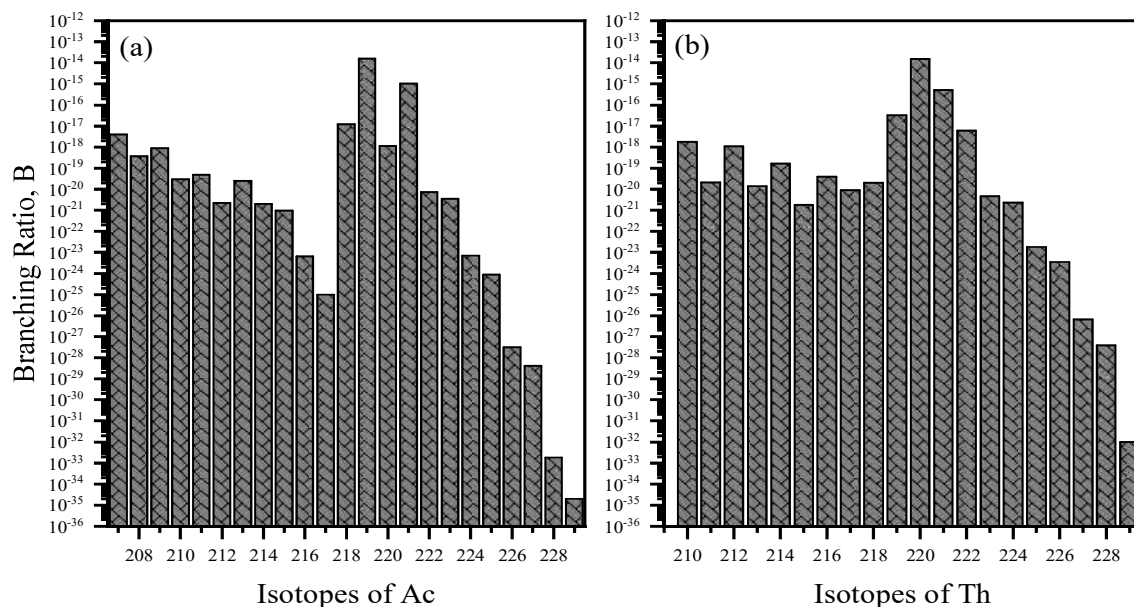


Figure 3.17: Branching ratio (B) for simultaneous 2α emission relative to α decay, plotted with respect to isotopes of (a) Ac and (b) Th.

cluster by disrupting pairing correlations. These findings indicate that our PCM results exhibit a consistent OES trend in α -preformation probabilities in consistent with the observations provided in Refs. [? ?].

The Q -value plot in Figure 3.15 (b) also shows noticeable pronounced staggering. While the Bethe-Weizsäcker mass formula predicts a generally smooth trend [? ? ?], our present work alongwith the experimental observations [? ?] reveal fluctuations that can be linked to pairing energies and shell structure. These variations in Q -value, when coupled with changes in P_0 , contribute directly to the observed staggering in decay half-lives.

An analogous investigation for thorium isotopes with $N \leq 126$ (not shown here to avoid redundancy) reveals a similar trend: odd- N Th isotopes exhibit reduced P_0 values and increased $\log_{10} T_{1/2}$, consistent with the behavior observed in Ac isotopes. Furthermore, a comparison between odd- Z and even- Z nuclei in Ac and Th isotopes shows that odd- Z nuclei systematically exhibit lower P_0 values for both α and 2α emissions compared to their neighboring even- Z nuclei. This trend is also evident in Figure 3.16, where odd- Z isotopes are found to have consistently longer half-lives for both α and 2α decays. In

conclusion, the observed odd-even staggering in α and 2α decay half-lives is predominantly governed by variations in preformation probabilities. This conclusion aligns well with the findings reported in Refs. [? ?].

Together, Figures 3.15 and 3.16 demonstrate that OES is a persistent and structurally driven feature across both α and 2α decay modes in actinide nuclei. The observed patterns validate the sensitivity of the PCM approach in capturing the nuclear structure effects and emphasize the influence of pairing correlations and shell effects, especially near closed neutron shells, in governing decay properties.

To examine the relative likelihood of simultaneous 2α emission in comparison to single α decay, Figure 3.17 presents the variation of branching ratios (B) as a function of mass number. Specifically, panel (a) shows the branching ratios for Ac isotopes, while panel (b) displays the corresponding values for Th isotopes. The branching ratio, quantitatively defined by Equation (14) (as introduced in the methodology section), represents the relative probability of the 2α decay channel with respect to the α -decay channel. It serves as a key indicator of the comparative dominance between competing decay modes in heavy nuclei. In both the cases, the branching ratio values are found to be negligibly small for all Ac and Th nuclei under study. This indicates that the α -decay is the dominant mode, while the 2α -emission, though present, is relatively suppressed. Of particular interest are the isotopes ^{219}Ac and ^{220}Th , which exhibit the highest branching ratios among their respective isotopes. These elevated values imply that these nuclei may possess more favorable conditions for simultaneous emission of two alpha particles. Such conditions may arise from enhanced Q -values for the 2α channel, as observed in Figure 3.15(b), or from specific nuclear structure effects that promote the formation of 2α emission. The identification of such isotopes with relatively higher branching probabilities thus offers valuable insights into the structural and energetic factors facilitating 2α decay in heavy nuclei.

Next, we have presented in Figure 3.18 the Geiger–Nuttall (GN) plots for both α and simultaneous 2α emissions from Ac and Th isotopes. These plots serve as a crucial tool to verify the linear relationship between the logarithm of the decay half-life and the inverse square root of the Q -value, which reflects the penetrability of the emitted cluster through

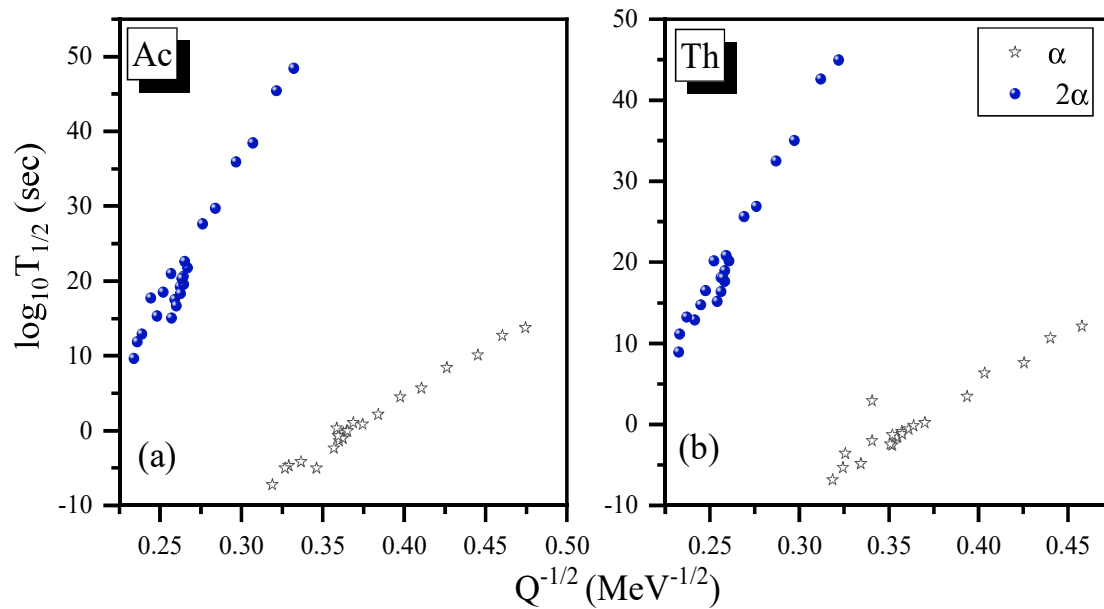


Figure 3.18: Geiger-Nuttall plots for α and 2α decay. Plotted are $\log_{10} T_{1/2}$ (s) vs $Q^{1/2}$ ($\text{MeV}^{-1/2}$) for different isotopes of (a) Ac and (b) Th.

the potential barrier.

The linear trends observed for both α and 2α decays across the isotopes of Ac and Th validate the applicability of PCM in describing both decay mechanisms. It is noteworthy that, for a given Q -value, the 2α decay modes generally exhibit larger half-lives (i.e., longer lifetimes) than the corresponding single α decays. This observation is consistent with the lower decay probabilities expected for heavier cluster emissions due to their larger Coulomb barriers and reduced penetrability.

Furthermore, the linear fits for both decay modes indicates that the underlying decay mechanism dominated by quantum tunneling, is preserved irrespective of the cluster size, though the 2α emission is kinetically less favored. The systematic behavior of the data points further reinforces the reliability of the calculated Q -values and half-lives in this work. Consequently, the present study lays a strong foundation for future experimental verification and encourages further theoretical investigations in reference to competing decay analysis of α , 2α and heavier cluster emission.

3.4 CONCLUSION

In this chapter, preformed cluster model is employed to study different ground state decay modes such as α decay, CR, HPR and SF from nuclei ranging $Z = 89-102$. The α -decay $\log T_{1/2}$ are calculated for two sets of chosen nuclei by optimising the neck length parameter, which is employed to calculate Q-value dependent first turning point i.e. $R_a(Q)$. The $R_a(Q)$ relations are employed to calculate α decay half-lives of other set of nuclei within chosen range and found to be in good agreement with the experimental data. The calculated preformation probability decreases with increase in the A (mass number) of parent nuclei. This may be associated with corresponding enhancement in P_o of fissioning region. The role of neutron shell closure at $N_2=126$ is clearly visible from the trend of the penetration probability (P). After the alpha decay analysis, the $R_a(Q)$ relations are obtained for CR and HPR decay modes. In the case of CR, the $R_a(Q)$ relation with deformed choice gives better agreement as compared to the spherical choice. Further, a comparative analysis of α -decay and spontaneous fission is made using the fragmentation potential and preformation distribution for extreme choice of nuclei (^{230}Th and ^{256}No) in range $Z=89-102$. The overall fragmentation structure remains same for both decay modes and the identified fission fragments are also similar. The mass distribution of the ^{230}Th and ^{256}No nuclei are studied, and it is observed that it changes from asymmetric to symmetric fragments. An attempt is made to identify the transition from asymmetric to symmetric distribution. In order to study the transition point, mass distribution of ^{252}Cf and ^{256}fm along with extreme nuclei in range $Z=89-102$ (^{230}Th and ^{256}No) is studied. After the analysis of fragmentation potential, probable fission fragments are identified. In addition to this, the total kinetic energy of these fission fragments is calculated and compared with experimental data. Also, the predictions of TKE are made for a chosen range of nuclei. Additionally, investigation of single α , simultaneous 2α , and heavier cluster decays in Ac and Th isotopes using the PCM. The study encompasses a broad range of isotopes, $^{207-229}\text{Ac}$ and $^{210-230}\text{Th}$ systematically analyzing their decay characteristics through the computation of Q-values, preformation factors, barrier penetrabilities, and half-lives. Among various nuclear interaction potentials

considered, the Modified Prox 88 potential was found to yield the most consistent results, and was therefore adopted for the comprehensive decay analysis. The decay systematics across these isotopes reveal an evolution in decay behavior: while α decay remains the dominant mode throughout, the 2α emission channel becomes comparatively more favorable in lighter isotopes. In contrast, heavier cluster decay, particularly ^{14}C emission is found to be more prominent in isotopes with higher neutron numbers. This trend aligns well with existing experimental observations, where the cluster radioactivity is predominantly reported in heavier isotopes. The computed half-lives demonstrate that isotopes such as ^{219}Ac and ^{220}Th are especially favorable for 2α emission, exhibiting the lowest decay half-lives for this mode. The branching ratio analysis supports this observation, indicating a gradual enhancement in the relative probability of 2α emission in certain isotopes, though α decay still prevails due to lower Coulomb barriers and higher penetrabilities. Additionally, significant even–odd staggering is observed in both half-lives and preformation factors, underscoring the sensitivity of decay processes to nuclear pairing and shell effects. The Geiger–Nuttall plots for both α and 2α emissions show strong linear correlations, reaffirming the quantum tunneling nature of these decay modes.

Following the detailed exploration of binary fission, attention is now directed toward the phenomenon of ternary fission. The subsequent chapter presents a comprehensive analysis of this process, encompassing its underlying mechanisms.

CHAPTER 4

Role of deformations and orientation effects in binary and ternary

decay of ^{252}Cf nucleus

4.1 Introduction

The first [?] direct observation of spontaneous binary fission of ^{252}Cf was achieved by using multiple Ge-detectors and implementing gammasphere. Besides binary fission, ternary fission of ^{252}Cf [?] was also observed as a probable spontaneous fission mode. Muga *et al.* [?] employed the nuclear emulsion technique to record and analyze the three fragments produced in the spontaneous ternary fission of ^{252}Cf . A wide range of light charged particles like ^3H , ^4He , ^6Li , ^{10}Be and ^{14}C are observed by various authors in ternary fission [?]. Goodin *et al.* [?] conducted a comprehensive investigation into the bimodal fission of ^{252}Cf . Their study observed various binary channels, including Xe-Ru and Ba-Mo, alongside ternary channels such as Zr- α -Ba, Xe- α -Mo, and Ru- α -Te. Ramayya *et al.* [?] identified different fragment channels in the cold spontaneous fission of binary (Ce+Zr, Tc+Cs, Ru+Xe, Ba+Mo, Te+Pd) and ternary (Nd+Kr+He, Ce+Sr+He, Ba+Zr+He, Xe+Mo+He, Te+Ru+He, Sn+Pd+He) decay of ^{252}Cf . Aside from light ternary particles, there is also the possibility of emission of heavy third fragments like C, O, N, Ne, Na, F, Mg, Al and Si reported by ref. [?]. Moreover, the prospect of True Ternary fission (TTF), characterized by the radioactive nucleus fragmenting into three entities of comparable masses was reported in [?]. It should be noted here that spontaneous TTF has not been experimentally observed but some experimental signature of induced TTF exists, where heavier third fragments were identified [?]. It has been observed that both

the fission fragments and the associated potential-energy surfaces are strongly influenced by the mass distribution of the fissioning system. Motivated by this dependence, the present work aims to investigate the binary and ternary fragmentation modes of ^{252}Cf , for further clarity of the decay dynamics of heavy nuclei.

Many experimental and theoretical [1–6] studies show that the most probable light ternary fragment is the alpha particle. The angular distribution analysis of light-charged-ternary particles indicates their formation in the neck region of two primary fission fragments. Consequently, these light particles are emitted predominantly in a direction perpendicular to the primary fission axis. The emission of a third fragment in this perpendicular direction is referred to as equatorial cluster tripartition (ECT). In contrast, when the third fragment is emitted along the fission axis, the process is termed collinear cluster tripartition (CCT) [7]. Recently, an extensive investigation of ternary fragments was carried out using the missing-mass technique with two FOBOS detector systems for the spontaneous fission of ^{252}Cf and neutron-induced fission of $^{235}\text{U}(\text{n, fff})$ [8–10]. The FOBOS setup detected fragments like Ni/Sn, while the determination of the third fragment was accomplished using the missing mass technique. As a result, three fragments with proton magic numbers $Z = 50, 28$, and 20 were observed, each possessing comparable masses. Earlier studies show that the ECT configuration is preferred for light-charged-accompanied fission while CCT is more suitable for the case of heavy-third fragment [11–13]. It may be noted that the deformations [14–16] play an important role in the binary fragmentation for the appropriate prediction of the favorable fragments and their respective yields [17]. Gupta *et. al* [18] calculated the fragmentation potential in view of the collision of two deformed and oriented nuclei, including deformations for coplanar and non-coplanar cases. Also, they have calculated the role of deformations and compact orientation in fusion-fission reaction [19]. Recently, excitation-energy-dependent potential energy surfaces for tripartition of ^{252}Cf were studied by taking orientation angles as 0^0-0^0 [20]. Many authors [21–23] investigated the importance of deformations and orientations in binary and ternary fission of various nuclei in the ground and excited states. This work is devoted to analyzing both decay modes simultaneously (binary and ternary) for ^{252}Cf nucleus by including the deformation

and orientation effect.

Based on the preceding discussion, the primary objective of this chapter is to achieve the following goals: (i) investigate the influence of deformations and orientations for binary and ternary channels. (ii) identify the most likely fission fragments for both binary and ternary decay scenarios. (iii) compare the ECT and CCT modes by considering the lighter and heavier fixed third fragments.

The structure of this chapter is organized as follows. Section 4.2 presents an exploration of the behaviour of binary and ternary fragmentation potentials, taking into account the effects of deformation and orientation. Also, the relative yield of different ternary combinations is analysed in this section. Lastly, Section 4.3 presents a conclusion of the observed outcomes. The research work presented in this chapter has been published in Ref. [?].

4.2 Discussion

This section presents a theoretical overview of the binary and ternary decay modes of ^{252}Cf nucleus. Section 4.2.1 analyses the binary and ternary fragmentation behaviour using deformations (up to β_2 -quadrupole deformations) and corresponding orientations (optimum and fixed). The resulting decay fragments are identified and subsequently compared with the available experimental findings as well as existing theoretical predictions. Section 4.2.2 presents a comparison between ECT and CCT configurations by taking third fragments as ^{30}Mg and ^{48}Ca using TCM. Further, Section 4.2.3 presents the relative yield for spontaneous ternary decay of ^{252}Cf by considering different A_3 combinations, i.e. ^4He , ^{30}Mg , and ^{48}Ca .

4.2.1 Binary and ternary decay of ^{252}Cf

In a nuclear reaction experiment, the positioning and choice of the detector can be determined by various factors like angles, energies involved in the reaction, and symmetry or asymmetry of the reaction products. Therefore, in the present work, an effort is made to encompass the diverse angles of the decaying fragments. An effort is made to understand how orientation angles change the mass distribution of the decaying fragments. In order to

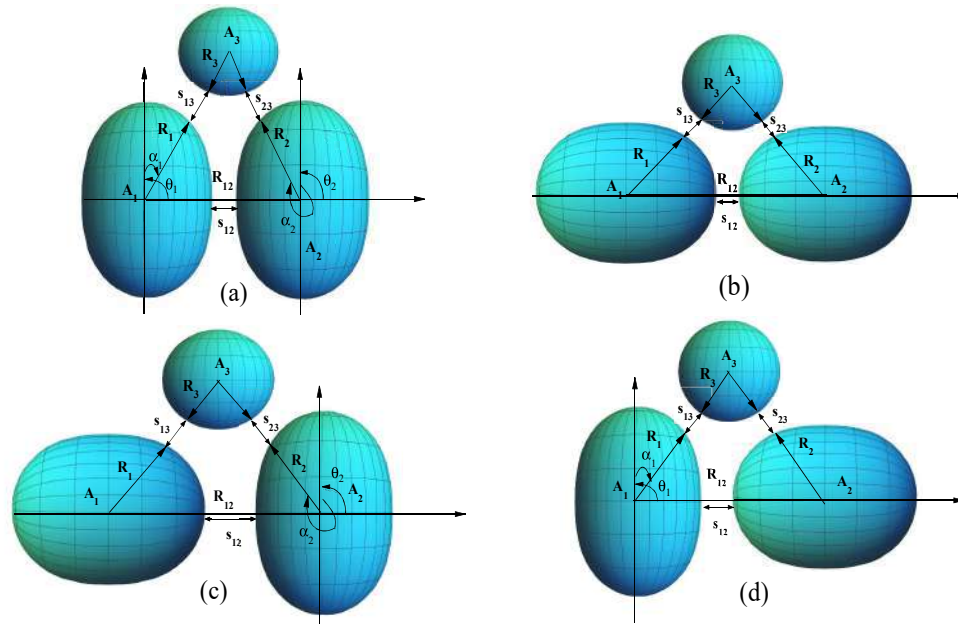


Figure 4.1: Schematic diagram of an equatorial configuration of two deformed heavy nuclei (A_1 and A_2) with the spherical third fragment ($A_3=^4\text{He}$) $(\theta_1, \theta_2) =$ (a) $90^\circ-90^\circ$ (b) $0^\circ-0^\circ$ (c) $0^\circ-90^\circ$ (d) $90^\circ-0^\circ$ with $\beta_{21}, \beta_{22} \geq 0$.

comprehend the nuclear dynamics of a radioactive nucleus, we undertake the calculations of the collective potential energy, also known as the fragmentation potential (as depicted in Eqs. 2.3 and 2.28 for binary and ternary decay, respectively). These results investigate the relative stability of decaying fragments by examining the profound valley within the fragmentation potential across all η values. This study incorporates deformation effects up to quadrupole (β_2) deformations, both with and without optimum orientation. Optimum orientation is determined based on the prolate and oblate shapes of β_2 deformations. For each case, the corresponding orientation angles are uniquely defined, which result in “hot-compact” and “cold-elongated” configurations (for a comprehensive explanation of optimal orientation pl. see [?]). In the present work, we denote hot-compact as compact and cold-elongated as elongated orientations. Furthermore, fixed orientations are characterized by specific values of θ_1, θ_2 ($(\theta_1, \theta_2 = (0^\circ-0^\circ), (0^\circ-90^\circ), (90^\circ-0^\circ)$ and $(90^\circ-90^\circ)$), independent of the shape of nuclei (shown in Fig. 4.1).

The binary fragmentation potential $V_R(\eta)$ (or V) is calculated using Eq. 2.3 and plotted with respect to fragment mass A_2 . Here, the values for quadrupole deformations are sourced from [?]. It is noteworthy to mention here that, during calculations, we

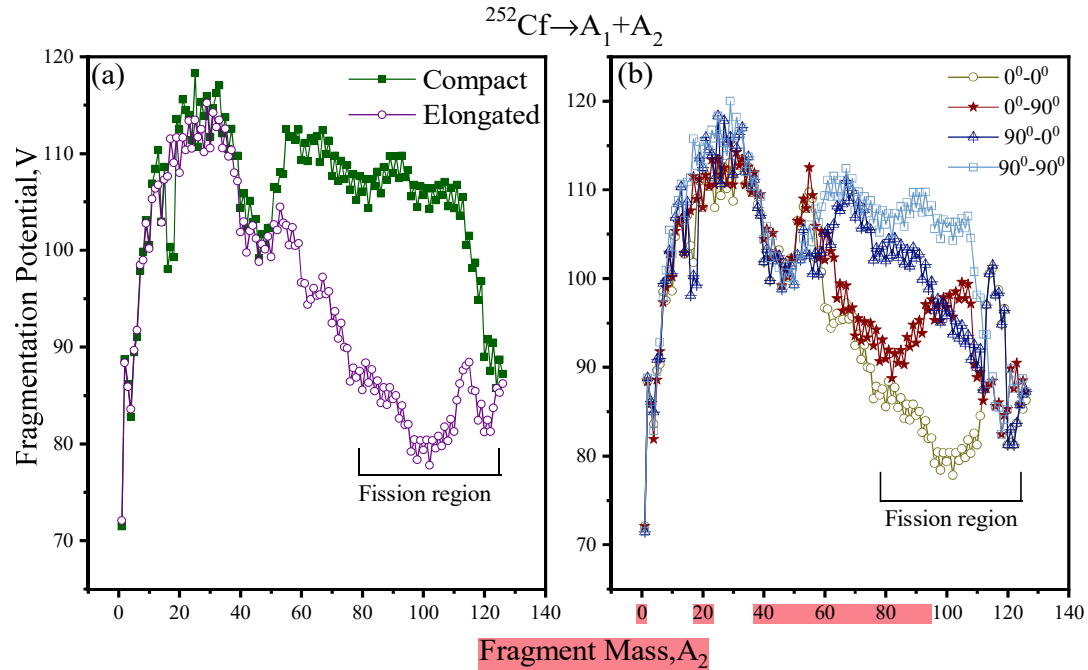


Figure 4.2: Binary fragmentation potential V (MeV) is plotted with respect to fragment mass number A_2 for ^{252}Cf calculated with inclusion of quadrupole deformation (β_2) (a) with optimum orientation (hot-compact and cold elongated) (b) with fixed orientation (where $(\theta_1, \theta_2) = (90^0-90^0), (0^0-0^0), (0^0-90^0)$ and (90^0-0^0))

observe a distinctive dip in the asymmetric fragmentation combinations such as $^{17}\text{B} + ^{235}\text{Np}$, $^{18}\text{C} + ^{234}\text{U}$, $^{54}\text{K} + ^{198}\text{Au}$, and $^{55}\text{K} + ^{197}\text{Au}$. These dips are attributed to exceedingly negative deformation values in one of the decaying fragments (^{17}B (-0.398), ^{18}C (-0.353), ^{54}K (-0.373), and ^{55}K (-0.398)). However, due to negligible magnitude of barrier penetration probability of these fragments, these dips have minimal impact on the overall fragmentation potential [?]. To rectify these dips within the fragmentation potential, the deformation parameters for these fragments (^{17}B , ^{18}C , ^{54}K , ^{55}K) are taken from the RMF model [? ?]. Further, using new deformation values for the above-mentioned nuclei, fragmentation potential is plotted as a function of A_2 shown in Fig. 4.2. The fragmentation potential depicted in Fig. 4.2(a) has been computed for both compact and elongated configurations. Whereas in Fig. 4.2(b) fragmentation potential is compared by taking fixed orientations where specific values of θ_1 and θ_2 are taken ($(\theta_1, \theta_2) = (90^0-90^0), (0^0-0^0), (0^0-90^0)$ and (90^0-0^0)). It shows that different orientations significantly affect the structure and magnitude of the fragmentation potential. The cold-elongated orientation (also called as pole-to-pole configuration [?]) yield lower magnitude of fragmentation potential as the interaction

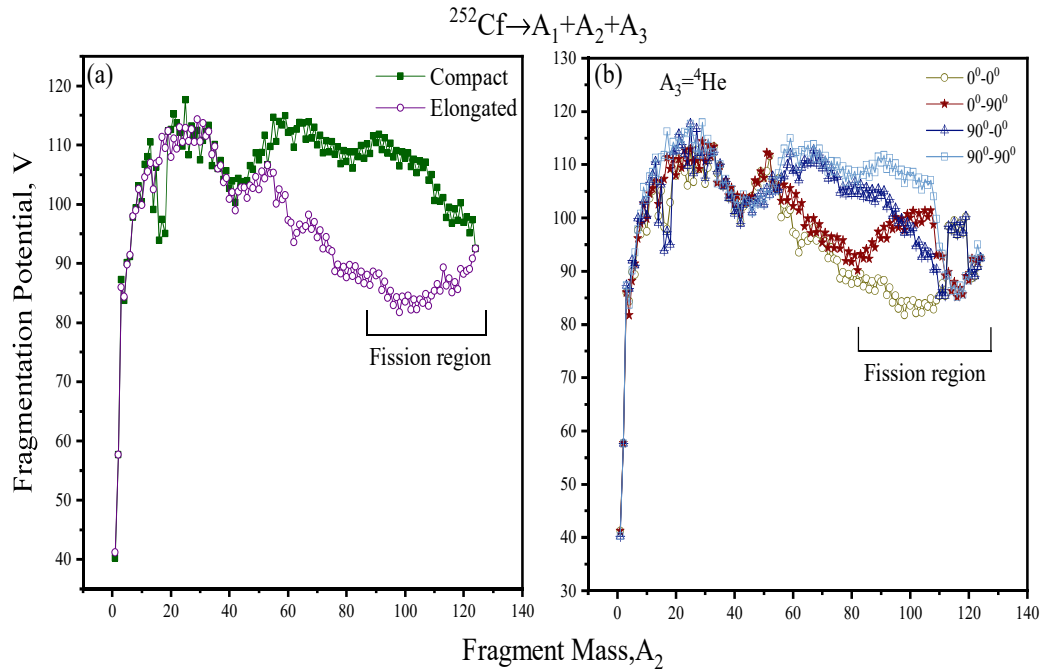


Figure 4.3: Ternary fragmentation potential V (MeV) for ^4He -accompanied fission is plotted as a function of fragment mass number A_2 with the inclusion of quadrupole deformation corresponding to (a) with optimum orientation (hot-compact and cold elongated) (b) with fixed orientation (where $(\theta_1, \theta_2) = (90^0-90^0), (0^0-0^0), (0^0-90^0)$ and (90^0-0^0))

radius is the largest. At this (pole-to-pole) orientation, the symmetry axis of both the deformed fragments lies along a straight line. Whereas compact configuration gives the highest potential as the interaction radius is lowest. A thorough examination of Fig. 4.2(a) shows that symmetric fission is prominent for compact configuration, whereas the dominance of asymmetric fission fragments is seen for elongated configuration. However, for fixed orientations, the symmetric and asymmetric fission fragments are observed. The configuration with angles 0^0-0^0 results in the formation of asymmetric fragments, whereas configurations with angles 0^0-90^0 , 90^0-90^0 , and 90^0-0^0 tend to give nearly symmetric fragments. This is due to the fact that most of the nuclei in the region ($100 \leq A_2 \leq 110$) are prolate deformed nuclei (as shown in Table 4.1), which with angle 0^0-0^0 will give a configuration where the interaction radius is maximum and hence potential energy (fragmentation potential) is minimum. On the other hand, the 90^0-90^0 configuration corresponds to the configuration with the smallest interaction radius, resulting in the highest potential energy. Whereas, the 0^0-90^0 and 90^0-0^0 configurations fall in between (with intermediate interaction radii) and, consequently result in intermediate potential

energy levels. However, for A_2 ranging from 116 to 126, the nuclei typically exhibit either oblate or spherical shapes. In this case, the 0^0-0^0 orientation minimizes the radius, resulting in an increase in potential energy, while the opposite holds true for the 90^0-90^0 configuration.

From the above analysis, it is evident that both deformation and orientation exert a substantial influence on the fragment mass distribution, since the fragmentation potential and the corresponding barrier height are strongly dependent on the chosen radius vector. The specific fission fragments identified within this region are detailed in the first and third columns of Table 4.1. Below all the fragments the combination of $(N_1, Z_1 + N_2, Z_2)$ with corresponding deformations values are mentioned in Table 4.1. As minimization with mass number is done, the mass fragments from $100 \leq A_2 \leq 116$ are identified. This shows a reasonable agreement with experimental observation of [? ?].

Among all the identified fission fragments the fragments like ^{100}Zr ($N_1=60, Z_1=40$)+ ^{152}Ce , ^{102}Zr ($N_1=62, Z_1=40$)+ ^{150}Ce , ^{103}Zr ($N_1=63, Z_1=40$)+ ^{149}Ce , ^{104}Zr ($N_1=64, Z_1=40$)+ ^{148}Ce , ^{106}Mo ($N_1=64, Z_1=42$)+ ^{146}Ba , ^{107}Mo ($N_1=65, Z_1=42$)+ ^{145}Ba , ^{108}Mo ($N_1=66, Z_1=42$)+ ^{144}Ba , ^{114}Ru ($N_1=70, Z_1=44$)+ ^{138}Xe , ^{116}Pd + ^{136}Te ($N_1=84, Z_1=52$) were experimentally observed [? ?]. Notably, the spherical magic shell closure ($Z=50, N=82$) significantly determines the favored fragment in the context of the hot-compact/ $(90^0-90^0, 0^0-90^0, 90^0-0^0)$ configuration. Conversely, the deformed magic shell closures ($Z=38, N=60$, and 62) and deformations play pivotal roles in instances of cold-elongated/ (0^0-0^0) configurations. Consequently, it can be ascertained that both spherical and deformed shell closures, alongside deformations up to quadrupole, are important for identifying the fragments of exit channel.

Furthermore, the possibility of ternary decay of the ^{252}Cf nucleus is examined within TCM [?]. The ternary fragmentation potential, evaluated using Eqn. 2.28 is computed for this nucleus using the assumption of an equatorial configuration [? ? ?] with fixed spherical third fragment ($A_3 = ^4\text{He}$) and plotted in Fig. 4.3 as a function of A_2 . The calculations are made at surface separation $s=1.0$ fm. This choice of surface separation (s) is taken in reference to [? ?].

This calculations are conducted both with and without optimum orientations, as ex-

4.2 Discussion

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Table 4.1: The most probable fission channels for binary (A_1+A_2) and ternary ($A_1+A_2+^4\text{He}$) fragment combination for ECT configuration of ^{252}Cf nucleus for optimum (compact and elongated) and without optimum (where $(\theta_1, \theta_2) = (90^\circ-90^\circ), (0^\circ-0^\circ), (0^\circ-90^\circ)$ and $(90^\circ-0^\circ)$) cases. The corresponding neutron (N), proton (Z) numbers and quadrupole deformations (β_{21}, β_{22}) of emitted fragments are presented below.

Cold-elongated/ $0^\circ-0^\circ$			Hot-compact/ $90^\circ-90^\circ/0^\circ-90^\circ/90^\circ-0^\circ$		
Binary	Ternary		Binary		Ternary
$^{100}\text{Zr}+^{152}\text{Ce}$	$^{92}\text{Kr}+^{156}\text{Nd}$		$^{116}\text{Pd}+^{136}\text{Te}$		$^{108}\text{Mo}+^{140}\text{Xe}$
(60,40+94,58)	(56,36+96,60)		(70,46+84,52)		(66,42+86,54)
(0.358,0.261)	(0.2280,0.279)		(-0.250,0.00)		(0.333,0.116)
$^{101}\text{Zr}+^{151}\text{Ce}$	$^{93}\text{Kr}+^{155}\text{Nd}$		$^{117}\text{Pd}+^{135}\text{Te}$		$^{109}\text{Mo}+^{139}\text{Xe}$
(61,40+93,58)	(57,36+95,60)		(71,46+83,52)		(67,42+85,54)
(0.368,0.252)	(0.265,0.279)		(-0.258,-0.008)		(0.334,0.100)
$^{102}\text{Zr}+^{150}\text{Ce}$	$^{94}\text{Kr}+^{154}\text{Nd}$		$^{118}\text{Pd}+^{134}\text{Te}$		$^{110}\text{Mo}+^{138}\text{Xe}$
(62,40+92,58)	(58,36+94,60)		(72,46+82,52)		(68,42+84,54)
(0.369,0.252)	(0.310,0.270)		(-0.240,0.00)		(0.335,0.00)
$^{103}\text{Zr}+^{149}\text{Ce}$	$^{95}\text{Rb}+^{153}\text{Pr}$		$^{119}\text{Ag}+^{133}\text{Sb}$		$^{111}\text{Mo}+^{137}\text{Xe}$
(63,40+91,58)	(58,37+94,59)		(72,47+82,51)		(69,42+83,54)
(0.380,0.235)	(0.329,0.270)		(-0.258,-0.008)		(0.336,-0.018)
$^{104}\text{Zr}+^{148}\text{Ce}$	$^{96}\text{Sr}+^{152}\text{Ce}$		$^{120}\text{Pd}+^{132}\text{Te}/^{120}\text{Pd}+^{132}\text{Sn}$		$^{112}\text{Ru}+^{136}\text{Te}/^{112}\text{Mo}+^{136}\text{Xe}/^{112}\text{Mo}+^{136}\text{Xe}/^{112}\text{Ru}+^{136}\text{Te}$
(64,40+90,58)	(58,38+94,58)		(72,48+82,50)		(68,44+84,52)
(0.381,0.216)	(0.338,0.261)		(0.135,0.00)/(-0.188,0.00)/(-0.188,0.00)		(70,42+82,54)
$^{105}\text{Nb}+^{147}\text{La}$	$^{97}\text{Sr}+^{151}\text{Ce}$		$^{121}\text{Cd}+^{131}\text{Sn}/^{121}\text{Pd}+^{131}\text{Te}/^{121}\text{Pd}+^{131}\text{Sn}$		(-0.258,0.00)/(0.337,0.00)/(0.337,0.00)
(64,41+90,57)	(59,38+93,58)		(73,48+81,50)		$^{113}\text{Nb}+^{135}\text{Cs}/^{113}\text{Nb}+^{135}\text{Cs}/^{113}\text{Ru}+^{135}\text{Te}$
(0.391,0.217)	(0.349,0.252)		(0.135,0.008)/(-0.162,0.00)/(-0.162,0.00)		(69,44+83,52)
$^{106}\text{Mo}+^{146}\text{Ba}$	$^{98}\text{Sr}+^{150}\text{Ce}$		$^{122}\text{Cd}+^{130}\text{Sn}$		(-0.258,-0.008)/(0.424,0.00)/(0.424,0.00)
(64,42+90,56)	(60,38+92,58)		(74,48+80,50)		$^{114}\text{Ru}+^{134}\text{Te}$
(0.361,0.199)	(0.357,0.252)		(0.108,0.00)		(70,44+82,52)
$^{107}\text{Mo}+^{145}\text{Ba}$	$^{99}\text{Y}+^{149}\text{La}$		$^{123}\text{Cd}+^{129}\text{Sn}/^{123}\text{Ag}+^{129}\text{Sb}/^{123}\text{Cd}+^{129}\text{Sn}$		(-0.258,0.00)
(65,42+89,56)	(60,39+92,57)		(75,48+79,50)		$^{115}\text{Rh}+^{133}\text{Sb}$
(0.352,0.183)	(0.368,0.244)		(0.116,0.00)/(-0.258,-0.008)/(0.116,0.00)		(71,44+82,51)
$^{108}\text{Mo}+^{144}\text{Ba}$	$^{100}\text{Zr}+^{148}\text{Ba}$		$^{124}\text{Cd}+^{128}\text{Sn}$		(-0.258,-0.008)
(66,42+88,56)	(60,40+92,56)		(76,48+78,50)		$^{116}\text{Pd}+^{132}\text{Sn}$
(0.333,0.164)	(0.358,0.236)		(0.00,0.00)		(70,46+82,50)
$^{109}\text{Mo}+^{143}\text{Ba}$	$^{101}\text{Y}+^{147}\text{La}$		$^{125}\text{Cd}+^{127}\text{Sn}/^{125}\text{Cd}+^{127}\text{In}/^{125}\text{In}+^{127}\text{In}$		(-0.250,0.00)
(67,42+87,56)	(62,39+90,57)		(77,48+77,50)		$^{117}\text{Pd}+^{131}\text{Sn}$
(0.334,0.155)	(0.379,0.217)		(0.00,0.00)/(0.00,0.00)/(0.053,0.027)/(0.053,0.027)		(71,46+83,50)
$^{110}\text{Mo}+^{142}\text{Ba}$	$^{102}\text{Zr}+^{146}\text{Ba}$		$^{126}\text{Cd}+^{126}\text{Sn}$		(-0.258,0.008)
(68,42+86,56)	(62,40+90,56)		(78,48+76,50)		$^{118}\text{Pd}+^{130}\text{Sn}$
(0.335,0.135)	(0.369,0.199)		(0.00,0.00)		(72,46+84,50)
					(-0.240,0.000)

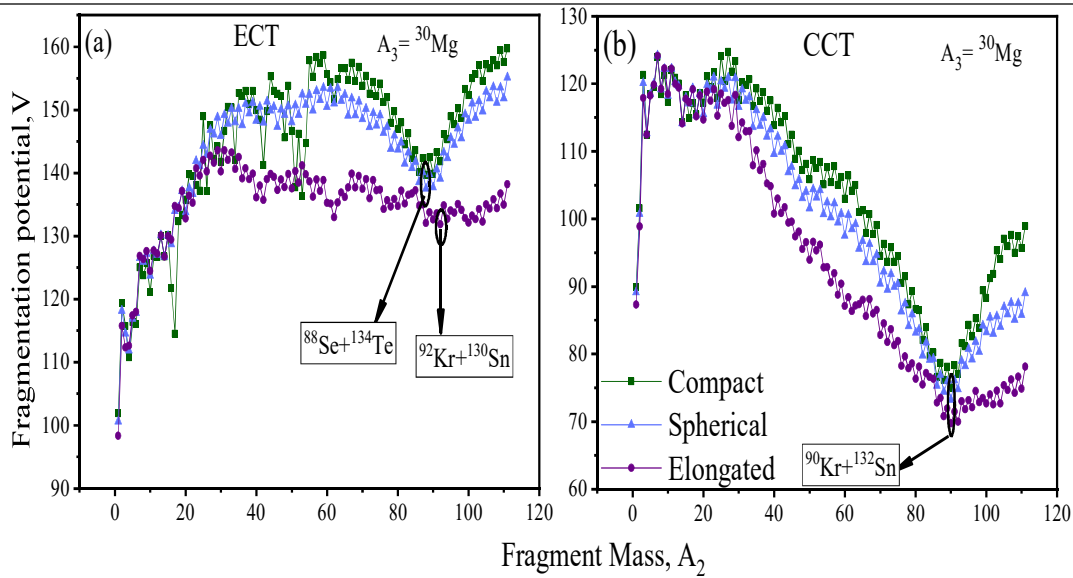


Figure 4.4: Ternary fragmentation potential (V) is plotted with respect to A_2 , for $A_3 = {}^{30}\text{Mg}$ with (a) ECT and (b) CCT configuration with optimum orientations (compact, elongated and spherical).

plained earlier. The resulting fragmentation potentials are depicted in Fig. 4.3, illustrating the relationship between fragment mass number A_2 and the potential energy. Fig. 4.3 (a) showcases the fragmentation potential between three fragments for both compact and elongated orientations. Similarly, in Fig. 4.3. (b), the fragmentation potential is calculated for fixed orientation. It shows that cold-elongated configuration gives lower potential as it corresponds to the higher interaction radius [?]. Whereas, the potential is relatively high for compact configuration due to the reduction in radius vector.

Evidently, the orientation degree of freedom significantly modifies the distribution of fission fragment distribution. This phenomenon is rooted in the diminishing influence of spherical shell effects with the incorporation of elongated orientations and the increasing influence of deformed shell closure. This interplay leads to symmetric mass distributions for the compact orientation and asymmetric distributions for the elongated orientation. However, for fixed orientations (where θ_1 and θ_2 are set of specific values), asymmetric and symmetric mass distributions can be seen. Notably, it should be emphasized that nuclei within the fission region ($92 \leq A_2 \leq 110$) are predominantly prolate-deformed nuclei, which potentially influence the fragmentation potential. Further, the minimized fission fragments for different sets of orientations are given in the second and fourth columns of Table 4.1, ${}^{103}\text{Zr}$ ($N=63, Z=40, \beta_2=0.380$) + ${}^{145}\text{Ba}$ ($N=89, Z=56, \beta_2=0.183$), ${}^{104}\text{Zr}$ ($N=64, Z=40, \beta_2=0.381$) + ${}^{144}\text{Ba}$ ($N=88, Z=56, \beta_2=0.164$), ${}^{105}\text{Nb}$ ($N=64, Z=41, \beta_2=0.391$)

4.2.2 Comparison between ECT and CCT configuration

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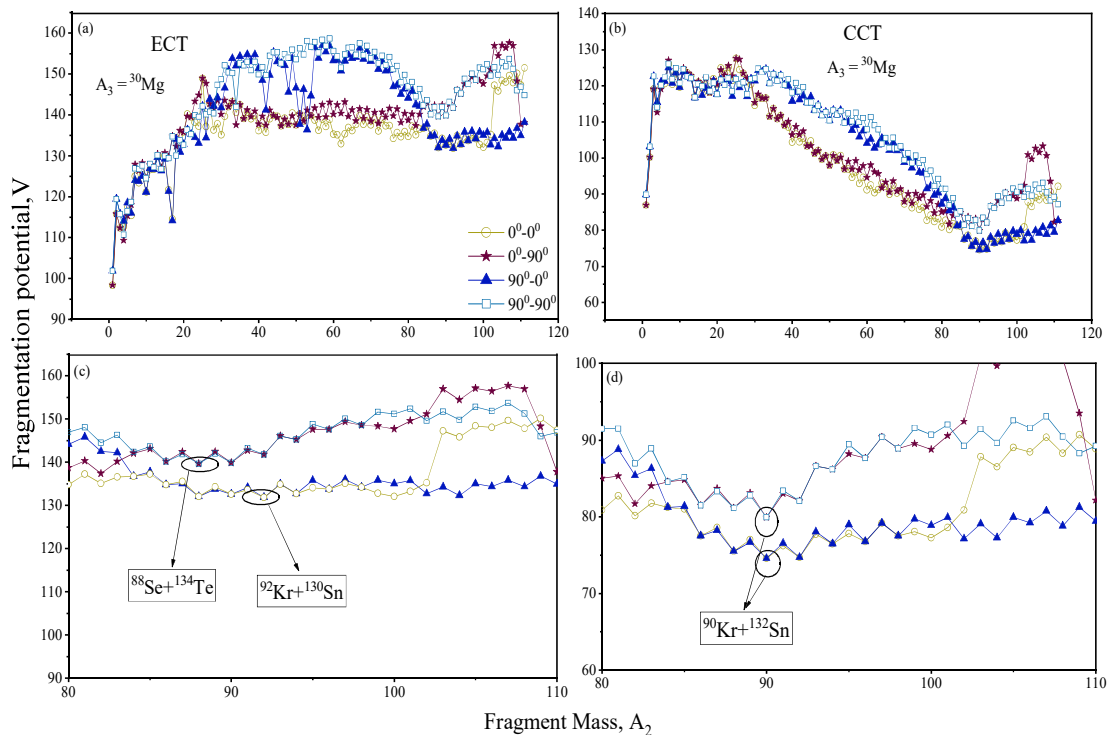


Figure 4.5: Ternary fragmentation potential (V) is plotted with respect to A_2 for $A_3 = {}^{30}\text{Mg}$ [(a) and (c)] using ECT and [(b) and (d)] CCT modes for $\theta_1, \theta_2 = (90^\circ-90^\circ), (0^\circ-0^\circ), (0^\circ-90^\circ), (90^\circ-0^\circ)$

???. A multitude of theoretical models and experimental data have concluded that the ECT configuration is more appropriate when the emitted third fragment is relatively light. Conversely, when dealing with a heavier third fragment, the CCT configuration becomes more probable [?].

To understand these decay modes, $A_3 = {}^{30}\text{Mg}$ is considered as a fixed third fragment and the three-body fragmentation potential of ${}^{252}\text{Cf}$ nucleus is plotted in Fig. 4.4 (a),(b) for ECT and CCT configurations, respectively. This figure shows that the structure of the fission valley and magnitude are significantly modified when one moves from ECT to CCT. This may be due to the larger interaction radius of CCT mode as the third fragment is in between the other two heavier fragments. It leads to decrease in Coulomb potential between two heavier fragments. Hence, the magnitude of the fragmentation potential for CCT mode is less as compared to ECT mode. A closer look of Fig. 4.4 shows that hot-compact orientation gives the highest magnitude of fragmentation potential, whereas cold-elongated orientation gives lowest. This is because the interaction radius

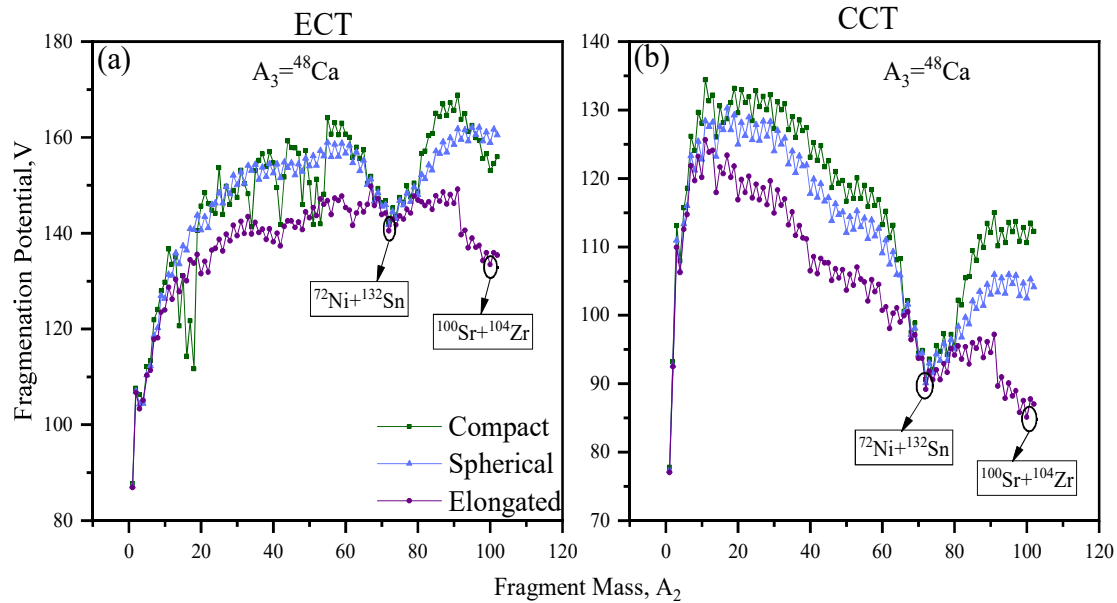


Figure 4.6: Ternary fragmentation potential $V(A_2)$ calculated with $A_3=^{48}\text{Ca}$ for ^{252}Cf radioactive nucleus using (a) ECT (b) CCT emission modes.

starts decreasing as one moves from elongated to compact orientations.

Note that the fragmentation potential's deep valley gives the most probable fragments compared to neighboring fragments. Consequently, a pronounced dip in the fragmentation potential appears for those fragments that possess magic proton or neutron numbers, or lie in the vicinity of spherical or deformed shell closures. From Fig. 4.4, one can see that for ECT configuration the most probable fission fragments for optimum compact orientation (and spherical case) ($^{88}\text{Se}(Z=34, N=54) + ^{134}\text{Te}(Z=52, N=82) + ^{30}\text{Mg}(Z=12, N=18)$) and elongated ($^{92}\text{Kr}(Z=36, N=56) + ^{130}\text{Sn}(Z=50, N=80) + ^{30}\text{Mg}(Z=12, N=18)$) are different. Whereas, for CCT configuration the most probable fragments remain the same i.e. $^{92}\text{Kr}(Z=36, N=56) + ^{130}\text{Sn}(Z=50, N=80) + ^{30}\text{Mg}(Z=12, N=18)$ for the compact, spherical and elongated case. Further, the different sets of angles where orientations are set to fix (as studied earlier) are calculated and shown in Fig. 4.5 for ECT and CCT modes. From Fig. 4.5 (a) and (b) one can observe that the fixed orientation choices significantly affect the fission valley's structure and magnitude for both configurations (ECT and CCT). The fragment combinations for ECT configuration with different fixed orientations are shown in Fig. 4.5 (c) i.e., for $0^0-0^0/90^0-0^0$ it is $^{92}\text{Kr}(Z=36, N=56) + ^{130}\text{Sn}(Z=50, N=80) + ^{30}\text{Mg}(Z=12, N=18)$, for $0^0-90^0/90^0-90^0$ it is $^{88}\text{Se}(Z=34, N=54) + ^{134}\text{Te}(Z=52, N=82) +$

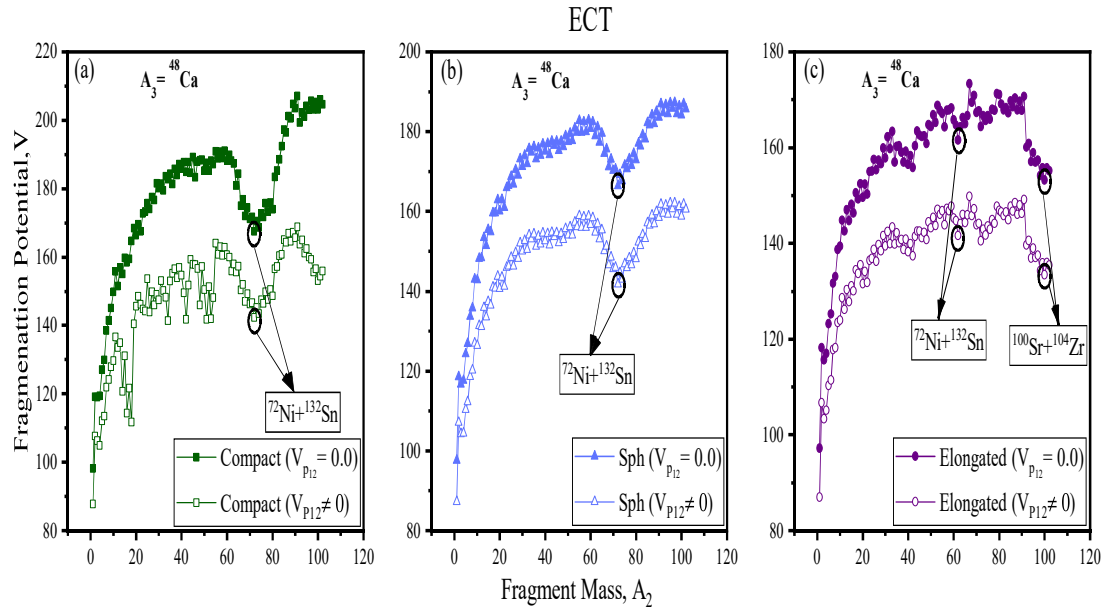


Figure 4.7: Ternary fission fragmentation potential plotted with respect to A_2 for ${}^{252}\text{Cf}$ nucleus with $A_3 = {}^{48}\text{Ca}$, for ECT mode comparing (a) compact (b) Spherical and (c) elongated by considering V_{P12} as zero and non-zero.

${}^{30}\text{Mg}$ ($Z=12$, $N=18$). Similarly, for different fixed orientations with CCT configuration, the fragments are shown in Fig. 4.5 (d) for different angles it is ${}^{90}\text{Kr}(Z=36, N=54) + {}^{132}\text{Sn}(Z=50, N=80) + {}^{30}\text{Mg}(Z=12, N=18)$. The proton and neutron numbers associated with each fragment combination are indicated, and all fragments exhibiting spherical or deformed magic shell closures are highlighted in bold. The fragments Kr and Sn with $A_3 = {}^{30}\text{Mg}$ are identified as the most probable fragments. Although there is no experimental evidence of these fragments, results show reasonable agreement with theoretical studies [?], as the identified fission fragments ${}^{88}\text{Se} + {}^{134}\text{Te}$ are the same.

Several experimental studies have indicated the presence of calcium as a third fragment in the decay of ${}^{252}\text{Cf}$ [? ?]. To delve deeper into this phenomenon, additional calculations have been conducted, wherein the third fragment is taken to be $A_3 = {}^{48}\text{Ca}$. To gain a more comprehensive understanding of the underlying processes the fragmentation potential for ECT and CCT cases. The calculations are done by considering spherical as well as deformed choice. The magnitude and structure are significantly modified when transitioning from the ECT to the CCT configuration, however, the identity of the most probable fission fragments remains essentially unchanged i.e., for compact

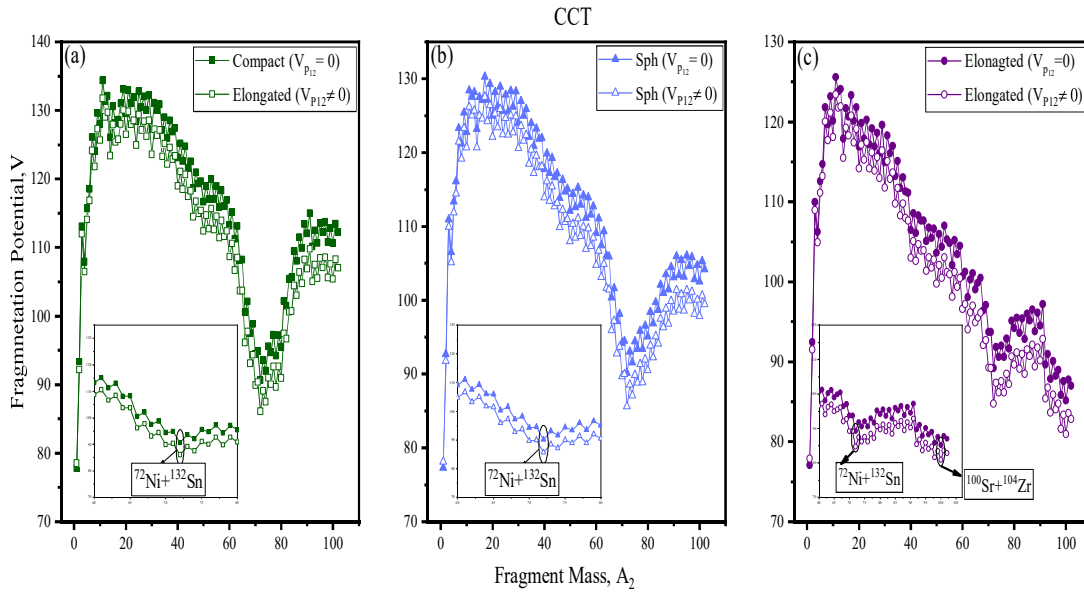


Figure 4.8: Ternary fission fragmentation potential plotted with respect to A_2 for ^{252}Cf with $A_3=^{48}\text{Ca}$ for ECT mode comparing (a) Compact (b) Spherical and (c) Elongated potentials by considering V_{P12} as zero and non-zero case.

(and spherical) $^{72}\text{Ni}(Z=28, N=44) + ^{132}\text{Sn}(Z=50, N=82) + ^{48}\text{Ca}(Z=20, N=28)$. Whereas for the cold-elongated (β_2 -deformed) arrangement, fragments are $^{72}\text{Ni}(Z=28, N=44) + ^{132}\text{Sn}(Z=50, N=82) + ^{48}\text{Ca}(Z=20, N=28)$ and $^{100}\text{Sr}(Z=38, N=62) + ^{104}\text{Zr}(Z=40, N=64) + ^{48}\text{Ca}(Z=20, N=28)$. From Fig. 4.6, one can observe that the deformations significantly change the magnitude and structure of the fragmentation potential for both configurations (ECT and CCT). This phenomenon arises from the fact that the interaction radius diminishes when transitioning from a cold-elongated to a spherical (or hot-compact) configuration.

This, in turn, significantly impacts the fragmentation potential, given its strong dependence on deformations and interaction radius. Notably, a pronounced dip becomes evident in the context of fragments ^{72}Ni and ^{132}Sn , considering the third fragment $A_3 = ^{48}\text{Ca}$, in both the spherical and deformed scenarios. This observation may be attributed to one of the fragments exhibiting shell closure and displaying no deformations. In contrast, another dip emerges in the fragmentation potential in the cold-elongated state, particularly in the case of the combination $^{100}\text{Sr} + ^{104}\text{Zr}$. This could be attributed to substantial deformations, as these nuclei exhibit a prolate shape, and one of the fragments demonstrate a deformed

magic number. A notable observation is that the favored fragments, driven by their lower fragmentation potential, remain consistent irrespective of the choice between the cluster tripartition configurations. Additionally, it's evident from the figures that the fission valley in the CCT case is more probable than that in the ECT case. This leads to the conclusion that the CCT configuration is more probable than the ECT configuration when considering the third fragment $A_3 = {}^{48}\text{Ca}$. This may be because the CCT has a larger interaction radius as the third fragment is heavy and lies in between the other two heavy fragments. CCT mode is studied by Pyatkov for ${}^{252}\text{Cf}$ nucleus [? ? ?] using the missing mass method. In these investigations, fission fragments such as Ni/Sn were detected through the utilization of the FOBOS setup at JINR. The third fragment was determined using the missing mass method. Consequently, the current calculations exhibit reasonable agreement with experimental data, with the most probable fragments being ${}^{132}\text{Sn} + {}^{48}\text{Ca} + {}^{72}\text{Ni}$.

Based on the preceding analysis, it can be deduced that the CCT configuration is better suited for the heavier third fragment. The fragmentation potential, which comprises binding energy, nuclear potential, and Coulomb potential, plays a crucial role in understanding the behavior of the fragments. Among these, the nuclear proximity potential short-range, is particularly relevant for understanding the interactions between the fragments. To gain further insight into the proximity potential, fragmentation potential with and without considering the proximity potential between two heavier fragments with different configurations, specifically the ECT and CCT configurations is calculated. The results are shown in Figs. 4.7 and 4.8. Here, V_{P12} represents the proximity potential between two fragments (A_1 and A_2). It's evident from the representation that in the ECT configuration, the contribution of V_{P12} is significant, as indicated by the substantial difference for deformed as well as spherical cases. In contrast, for the CCT configuration, the influence of V_{P12} is negligible, with minimal difference between the potentials. This can be attributed to the substantial inter-fragment distance between A_1 and A_2 , resulting in a reduction of potential within the CCT setup. This effect becomes particularly pronounced for heavier third fragments. In the specific scenario described here, the third fragment is taken as ${}^{48}\text{Ca}$. Hence, one can conclude that the proximity potential plays more relatively salient

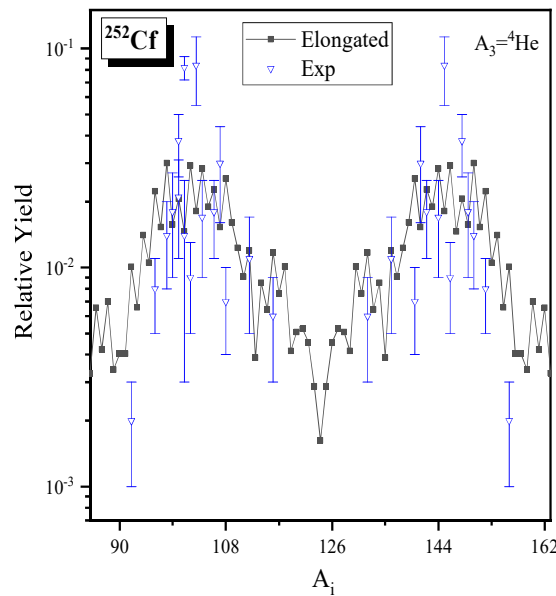


Figure 4.9: The calculated relative yield for the ternary fission of ^{252}Cf nucleus for ^4He accompanied ternary fission is compared with experimental data.

role in the case of CCT configurations.

4.2.3 Ternary fragmentation yields

Further, based on theoretical [? ? ? ? ?] as well as experimental [?] investigations, the relative yield for the spontaneous ternary fission of ^{252}Cf is studied by taking various choices of the third fragment. The relative yield corresponding to each fission valley is determined as the ratio of the penetration probability of a specific fragmentation channel to the sum of the penetration probabilities over all possible channels, as defined in Eq. 4.9. In the present study, we calculate the yield by considering β_2 deformations with cold-elongated orientation, employing the ECT configuration (shown in Fig. 4.1 (b)), taking $A_3=^4\text{He}$ for the spontaneous ternary fission of ^{252}Cf and is illustrated in Fig. 4.9. It is relevant to note that the nuclei in the region $92 \leq A_2 \leq 110$ exhibit predominantly prolate-deformed shapes. This dominance strongly influences the elongated yield as the interaction radius increases for these fragments. The specific fragments identified in this context are highlighted and detailed in Table 4.1. Fig. 4.9 presents the comparison of calculated ternary yield for the ^4He spontaneous ternary fission of ^{252}Cf with available experimental data [?], and it shows a reasonable agreement with data. Furthermore,

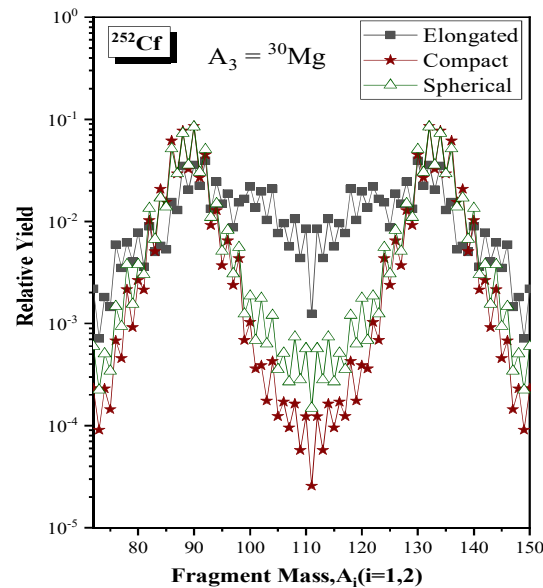


Figure 4.10: The calculated relative yield for ternary fission of ^{252}Cf by taking $A_3 = {}^{30}\text{Mg}$ considering ECT configuration is plotted with respect to fragment mass numbers A_1 and A_2 . Comparing elongated, compact and spherical orientations.

yield for $A_3 = {}^{30}\text{Mg}$ and ${}^{48}\text{Ca}$ for spherical, elongated and compact orientation is shown in Figs. 4.10 and 4.11.

It's essential to highlight that lighter third fragments favor the ECT configuration. Consequently, for $A_3 = {}^4\text{He}$, ECT is utilized to compute the relative yield. However, for heavier third fragment both ECT and CCT configurations become significant. In order to understand both the processes, relative yield of ${}^{30}\text{Mg}$ is calculated using ECT and CCT is employed for relatively heavier third fragment ${}^{48}\text{Ca}$. In Fig. 4.10, compact, elongated and spherical orientations, are presented by taking ECT configuration, revealing a preference for asymmetric distribution. For the elongated orientation, the most probable fragments are ${}^{92}\text{Kr}(Z=36, N=56) + {}^{130}\text{Sn}(Z=50, N=80) + {}^{30}\text{Mg}(Z=12, N=18)$, while for the compact and spherical configuration the most probable fragments are ${}^{90}\text{Kr}(Z=36, N=54) + {}^{132}\text{Sn}(Z=50, N=80) + {}^{30}\text{Mg}(Z=12, N=18)$. These findings exhibit reasonable agreement with theoretical data [?], particularly in observing asymmetric distribution in the tripartition of the ^{252}Cf nucleus with $A_3 = {}^{30}\text{Mg}$. Further, Fig. 4.11 illustrates the relative yield with $A_3 = {}^{48}\text{Ca}$, encompassing compact, elongated and spherical orientations by taking CCT configuration (as shown in Fig. 2.3 (b)). Significantly, asymmetric

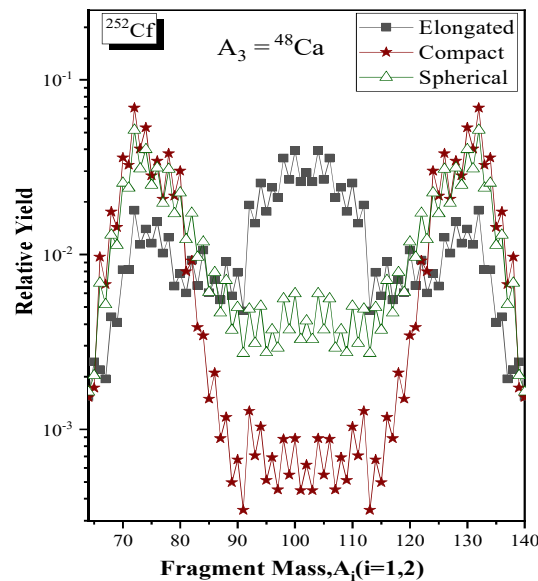


Figure 4.11: The calculated relative yield for the ^{48}Ca accompanied ternary fission of ^{252}Cf nucleus using elongated, spherical and compact orientations by considering CCT configuration.

peaks dominate, while an additional symmetric peak emerges in the case of elongated orientations. For the asymmetric peak, the most probable fragments consist of ^{72}Ni ($Z=28$, $N=44$) + ^{132}Sn ($Z=50$, $N=82$) + ^{48}Ca ($Z=20$, $N=28$). On the other hand, the most probable fragments for the symmetric peak include ^{100}Sr ($Z=38$, $N=62$) + ^{104}Zr ($Z=40$, $N=64$) + ^{48}Ca ($Z=20$, $N=28$). The obtained results show reasonable agreement with the available experimental data [? ? ?] data. Therefore, we can conclude that the calculated relative yield for elongated orientation for $A_3 = ^4\text{He}$ fragment show better agreement with experimental data (see Fig.4.10). Therefore, it is expected that elongated orientation criteria should work for heavier third fragments i.e. ^{30}Mg and ^{48}Ca . Further, the spherical and compact orientations are reported for comparative analysis and future reference/validations. This observation underscores the relevance of deformations and shell effects in identifying ternary fission fragments in view of different orientation criteria.

4.3 Conclusion

The spontaneous binary and ternary fission of ^{252}Cf is studied within PCM and TCM, respectively. For both, the fragmentation potential is computed by including β_2 defor-

mations with in possible orientation. For both decay modes, the fission fragment mass distribution shifts from a symmetric mass distribution to an asymmetric one when transitioning from the optimum hot-compact configuration to the optimum cold-elongated configuration. This behavior arises from the reduction in the interaction radius when moving from the elongated optimum configuration to the compact-optimum configuration. The β_2 deformed compact/ 90^0 - 90^0 / 0^0 - 90^0 / 90^0 - 0^0 configuration shows the dominance of symmetric and near symmetric decay channels with prominent influence of spherical magic shell closure. However, for elongated/ 0^0 - 0^0 orientation (β_2 deformed) approach shows asymmetric distribution with the dominance of deformed magic shell closure.

It is observed that the magnitude and structure of fragmentation potential is significantly modified when one shifts from ECT to CCT configuration. Moving from the case of intermediate ($A_3 = {}^{30}\text{Mg}$) to heavier ($A_3 = {}^{48}\text{Ca}$) third fragment, the CCT mode starts competing with the ECT one. The heavier third fragment shows a prominent dip in CCT mode as the interfragment distance is large and results in a lower magnitude of proximity and Coulomb potential. This dip corresponds to ${}^{72}\text{Ni}(Z=28, N=44) + {}^{132}\text{Sn}(Z=50, N=82) + {}^{48}\text{Ca}(Z=20, N=28)$. Whereas, additional dip at ${}^{100}\text{Sr}(Z=38, N=62) + {}^{104}\text{Zr}(Z=40, N=64) + {}^{48}\text{Ca}(Z=20, N=28)$ is observed for elongated configuration. In general, one of the decaying fragments is associated with neutron/proton shell closure, which is consistent with experimental observations [? ? ?]. In addition to this, relative yield of different tri-partition combinations is studied and compared with experimental data. The results obtained are aligned with the studies done so far. It is concluded that the deformations and orientations play a significant role in identifying the binary and ternary fission fragments. Hence, various orientation prospects are explored which may impart useful insights for future understanding of reaction dynamics on theoretical as well as experimental front.

After the detailed exploration of binary and ternary fission processes, attention is now directed toward the phenomenon of multicluster emission, which encompasses quaternary fission. The study of multicluster fission is of considerable significance, as it bridges the understanding between conventional fission modes and highly complex fragmentation mechanisms. In the subsequent chapter, a comprehensive analysis of this process is

presented, including its possible fragment combinations, potential energy surface configurations, and theoretical interpretations aimed at elucidating the underlying mechanisms governing such rare decay modes.

CHAPTER 5

Exploration of multi-fragment emission from ^{252}Cf nucleus in collinear configuration mode

5.1 Introduction

The presence of ternary fission was identified in [?] where the long-range alpha-particles were emitted in coincidence with the two principal fission fragments. The literature indicates that the ternary yield is approximately of the order 10^{-3} as compared to binary fission [? ? ?]. Experimental studies [?] revealed that light charge particles (LCPs) are responsible for nearly 97% of the total yield. The decay process involves the emission of alpha particles and tritons as the LCPs are accompanied with two fission fragments. Furthermore, a relatively rare process [? ?] known as quaternary fission also exists. Quaternary fission can be categorized in two ways. One is called spontaneous quaternary decay, where four decaying fragments emerge simultaneously from the radioactive nucleus. On the other hand, the pseudoquaternary fission process is a sequential, two-step decay mechanism. In the first stage, three primary fragments are emitted, with one of them being unstable. In the second stage, this unstable fragment undergoes a subsequent decay into two lighter fragments, thereby completing the quaternary-like process. The experimental investigations [? ?] and theoretical analyses [?] provide clear evidence for the occurrence of quaternary and ternary fission in $^{235}\text{U}(n,f)$ induced by thermal neutrons and in the spontaneous fission of ^{252}Cf . Quaternary fission yields are notably higher in spontaneous ^{252}Cf fission, emitting particles like (α,α) , (α,t) , and (t,t) with two heavy fragments. Recent experimental work conducted by Pytafov *et al.* [?] has explored the

multibody decay, shedding light on the true quaternary decay (true is used to underline that all the decay products have comparable size) of ^{252}Cf .

To understand these complex phenomena, many theoretical [? ? ?] models were introduced where one, two and three necks are formed, leading to binary, ternary and quaternary fission. Such decay routes are characterized by highly elongated pre-scission configurations of the parent nucleus. These models highlight the significant role of shell effects in multi-body decay, particularly emphasizing the strong shell effects associated with the doubly magic heavy fragment ^{132}Sn . The relevance and influence of shell effects is crucial in understanding the intricate dynamics of nuclear fragmentation process.

The aim of the present chapter is to (a) investigate the possible decay pathways (binary, ternary and quaternary) of ^{252}Cf nucleus. (b) analyse the fragmentation potential by considering equatorial and collinear configurations. (c) identification of the most probable fragments resulting from ternary and quaternary fission from ^{252}Cf nucleus. (d) to find a comparative analysis of ternary and quaternary fission, by taking a range of middle fragments. For quaternary fission both identical and non-identical third and forth particles are considered. These investigations collectively enhance the understanding of the decay behaviour of ^{252}Cf , particularly the feasibility and characteristics of ternary and quaternary fission pathways compared to binary fission. The study aims to highlight key fragment compositions and their implications in nuclear decay dynamics of ^{252}Cf nucleus.

The outline of the chapter is as follows: Section 5.2 delves into the discussion of the fragmentation potential of binary, ternary and quaternary fission of ^{252}Cf nucleus. The most probable fragments are identified and discussed. Finally, the conclusions are summarized in Section 5.3. The results presented in this chapter are published in ref. [? ? ?]

5.2 Discussion

This section provides a theoretical overview of the decay dynamics of ^{252}Cf nucleus. First, Subsection 5.2.1 investigates the competing binary and ternary decay of ^{252}Cf . Section 5.2.2 presents a detailed analysis of quaternary fission along the fission axis, where all possible arrangements are considered in collinear configuration. The most favourable arrangements and corresponding fragment combinations are identified, followed by a

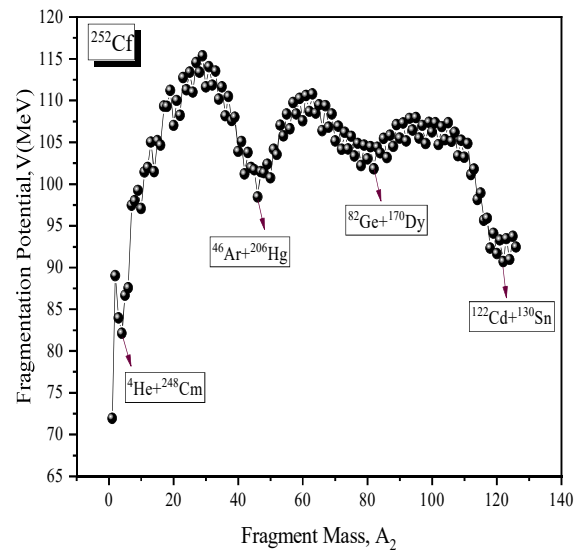


Figure 5.1: The variation of binary fragmentation potential as a function of fragment mass A_2 for the decay of ^{252}Cf for touching configuration.

comparative analysis of ternary and quaternary fission. Section 5.2.3 investigates the role of surface separation in the multicluster emission. Further, section 5.2.4 extends the analysis to quaternary fission with non-identical middle fragments, including light charged particle emission. A comparison between collinear and equatorial configurations is also performed for both ternary and quaternary fission processes.

5.2.1 Binary Versus Ternary fission of ^{252}Cf

In various experimental [?] and theoretical analysis [?], the probable disintegration paths of the ^{252}Cf nucleus have been examined. As expected, the two-body decay mechanism or the binary fission is registered with highest yield as compared to other multi-cluster emission modes. Initially, to study the binary emission modes of ^{252}Cf , the same is explored in terms of the fragmentation potential. The fragmentation potential is evaluated as a function of mass asymmetry(η) and is plotted as a function of A_2 , as shown in Fig. 5.1. A minimum in the fragmentation potential identifies the most probable fragment and its corresponding complementary partner. Therefore, the most probable fragment combinations from Fig. 5.1 are $^4\text{He}(\text{N}=2, \text{Z}=2) + ^{248}\text{Cm}$ ($\text{N}=152, \text{Z}=96$), $^{46}\text{Ar}(\text{N}=28, \text{Z}=18) + ^{206}\text{Hg}$ ($\text{N}=126, \text{Z}=80$), $^{82}\text{Ge}(\text{N}=50, \text{Z}=32) + ^{170}\text{Dy}$ ($\text{N}=104, \text{Z}=66$) + $^{122}\text{Cd}(\text{N}=74, \text{Z}=48) + ^{130}\text{Sn}$ ($\text{N}=80, \text{Z}=50$). These observed minima

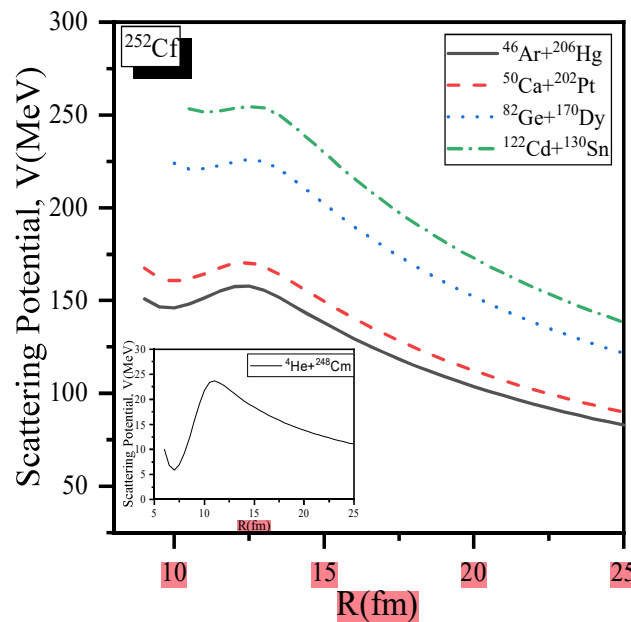


Figure 5.2: Calculated scattering potential as a function of R-co-ordinate for the α -, CR, HPR and SF decay paths for ^{252}Cf .

in the fragmentation potential are primarily attributed to underlying shell-closure effects. In each identified case, at least one of the fragments possesses a magic proton or neutron number (highlighted in above text). The most probable fragments i.e. ^4He , ^{46}Ar , ^{82}Ge and ^{122}Cd correspond to four exit modes such as α -particles, CR, HPR and SF. These observations show a reasonable agreement with experimental [? ?] and theoretical [? ? ?] studies. The results further indicate that the deepest minimum in the fragmentation potential corresponds to the emission of an alpha particle (^4He) in the binary decay of ^{252}Cf , it signifies that the α -channel forms the most probable decay mode. The main highlight of this study is that the probable binary decay modes such as α , CR, SF etc are explored in one set of calculation, by adopting collective clusterization method.

After the fragmentation analysis, the barrier characteristics for the most probable decay channels are studied by calculating scattering potential (calculated using $V = V_c + V_p$) of respective decay channels and plotted as a function of range (R) shown in Fig. 5.2. As evident from Fig. 5.2, the scattering potential undergoes significant variation along the decay paths associated with α - (^4He), cluster (^{46}Ar and ^{50}Ca), heavy cluster (^{82}Ge) and SF (^{122}Cd) for ^{252}Cf . Notably, the lower barrier height observed for α -decay implies that it is a more probable decay mode compared to paths with higher barrier heights,

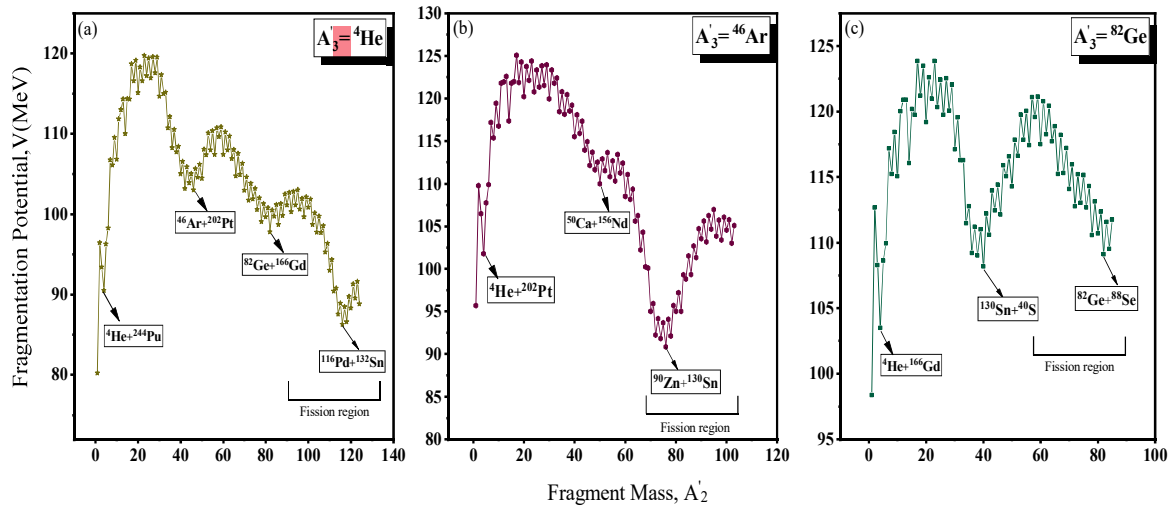


Figure 5.3: The calculated fragmentation potential for ternary fission of ^{252}Cf for different third fragments $A_3 =$ (a) ^4He , (b) ^{46}Ar and (c) ^{82}Ge is plotted with fragment mass number A_2' .

where the probability of decay decreases accordingly. This trend underscores a greater likelihood of decay involving lighter fragments than the heavier ones. Consequently, the scattering potential results align with those obtained from the fragmentation potential analysis, affirming that α -decay remains the most probable decay mode in the binary decay of ^{252}Cf . Interestingly, alpha particle is also registered with higher yield along with two heavy fragments in ternary fission experiments [?]. Hence, it will be of interest to do a comparative analysis of the binary and ternary fragmentation structures. In the next step, the ternary fragmentation potential is calculated by keeping ^4He , ^{46}Ar and ^{82}Ge as fixed fragments and plotted in Fig. 5.3 as a function of fragment mass A_2' .

These calculations are done at the touching configuration. It may be noted here that the co-linear cluster tripartition is used for the ternary fission analysis. This is due to the formation of longer neck during decay process [?]. Also, recent work [?] by our group shows the importance of CCT configuration and is probable for ternary fission. Therefore, the further analysis is done by using the CCT configuration. As stated above, the choice of the different third fragment is taken from the deep minima in the fragmentation potential of binary fission such as ^4He , ^{46}Ar and ^{82}Ge . From Fig. 5.3, one can see that the most probable fission fragments for $A_3' = ^4\text{He}$ are $^4\text{He}(Z=2, N=2) + ^{244}\text{Pu}(Z=94, N=150)$, $^{46}\text{Ar}(Z=18, N=28) + ^{202}\text{Pt}(Z=78, N=124)$,

$^{82}\text{Ge}(Z=32, N=50) + ^{166}\text{Gd}(Z=64, N=102) \rightarrow ^{132}\text{Sn}(Z=50, N=82) + ^{116}\text{Pd}(Z=46, N=70)$ for ^{46}Ar are $^4\text{He}(Z=2, N=2) + ^{202}\text{Pt}(Z=78, N=124)$, $^{50}\text{Ca}(Z=20, N=30) + ^{202}\text{Pt}(Z=78, N=124)$, $^{130}\text{Sn}(Z=50, N=80) + ^{90}\text{Zn}(Z=30, N=60)$, and for ^{82}Ge are $^4\text{He}(Z=2, N=2) + ^{166}\text{Gd}(Z=64, N=102)$, $^{130}\text{Sn}(Z=50, N=80) + ^{40}\text{S}(Z=16, N=24)$ respectively. It also shows that the structure and magnitude of the fission valley are significantly modified when one moves from a lighter to a heavier third fragment. Further, it can also be seen that for $A_3 = ^{82}\text{Ge}$, another dip emerges in the fragmentation potential, particularly at $^{88}\text{Se}(Z=34, N=54) + ^{82}\text{Ge}(Z=32, N=50)$. This could be attributed to magic shell closure, as at least one of the nuclei exhibits magic shell closure, lowering the potential energy. From Fig. 5.3(a)-(c) it can be concluded that the minima in the fission region is more prominent. This is due to the presence of neutron/proton magic nuclei ^{132}Sn , ^{130}Sn and $^{130}\text{Sn}/^{82}\text{Ge}$ respectively for $A_3 = ^4\text{He}$, ^{46}Ar and ^{82}Ge . Therefore, for $A_3 = ^4\text{He}$ the most probable combination is $^{132}\text{Sn} + ^{116}\text{Pd}$. These fragment combinations have also been observed theoretically and experimental [? ?].

Note that the magnitude of α -accompanied ternary fission is minimum (see Fig. 5.3(a)). Which indicate the most probable decay mode in ternary decay of ^{252}Cf nucleus. Hence, it can be inferred that alpha decay dominates in both binary and ternary decay processes. It is also worth noting that recent experiments on collinear cluster tri-partition (CCT) of the ^{252}Cf [? ?] nucleus have identified ^{48}Ca , along with neighboring nuclei, as a third fragment in these fission events. To gain a deeper understanding of such phenomena, a detailed analysis is presented in the next section. The quaternary fission of ^{252}Cf is also explored.

5.2.2 Ternary and Quaternary fission of ^{252}Cf

Recently, both experimental [? ? ?] and theoretical [? ?] findings have suggested the intriguing possibility of four, five or six nuclei occurring within the radioactive nucleus. In the ternary fission of heavy nuclei, the emission of light charged particles such as proton, neutron, deuteron and other isotopes of He, Li, Be, B, C, N, O takes place along with two heavy fission fragments. Additionally, heavy particles like Ne, Na, Mg, Ar and Ca have been detected in recent experiments, alongside the emission of two fission

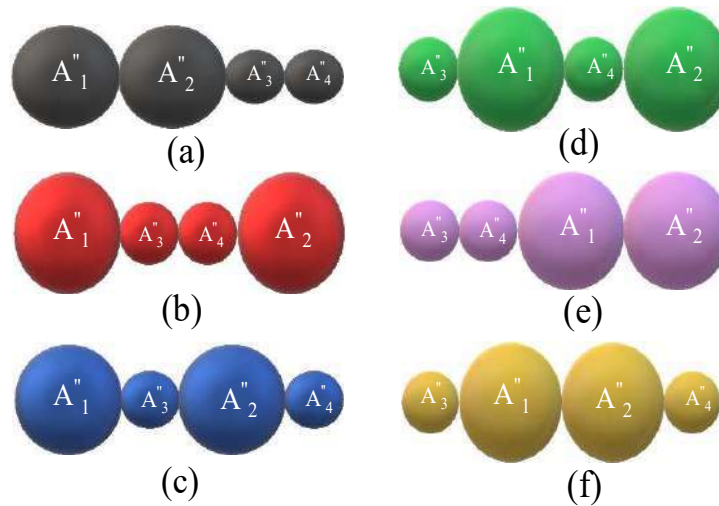


Figure 5.4: Possible configurations for emission of two light charged particles from radioactive nucleus.

fragments. Further, the combination of two light-charged particles like (α, α) , (α, t) has also been observed with the emission of two fission fragments. These observations suggest the occurrence of multi-cluster emission within a radioactive nucleus. This phenomenon involves various combinations of light and heavy fragments, contributing to the overall decay process. In view of this, a comprehensive analysis of ternary and quaternary fission of ^{252}Cf nucleus is worked out.

As a first step, the configuration of decaying fragments is examined. The study of different configurations [? ?] in the decay process of ^{252}Cf provides a crucial information about the underlying mechanisms, potential energy landscapes, and the likelihood of the specific decay modes. Numerous studies [? ?] have been conducted to gain a deeper understanding of the mechanisms underlying the multi-cluster configurations in the exit channel. The study finds that specific configurations, especially those involving multiple alpha ($2\alpha, 3\alpha, 4\alpha$) particles, are preferred. Each configuration is associated with potential energy values as the different fragment arrangements lead to differences in the interactions involved. The lower magnitude corresponds to a more stable emission mode. Therefore, configurations with lower potential energy are more likely to occur during the decay process.

As the present study focuses on (multi-cluster emission) quaternary decay process, various configurations of the fragments aligned along the same axis are examined. Specifically,

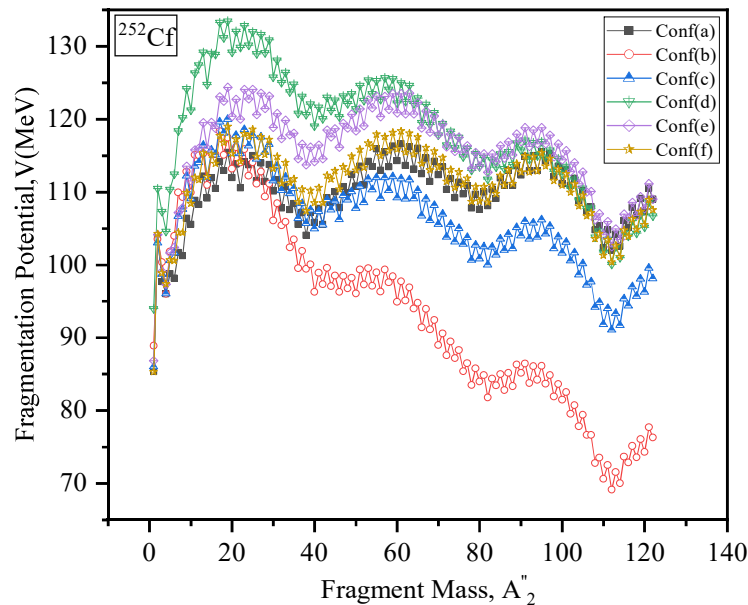


Figure 5.5: The fragmentation potential V as a function of fragment mass A_2 for different probable configurations (pictorially shown in Fig. 5.4) at touching configuration.

investigation is done for scenarios involving two light particles (α - α), denoted as A_3'' and A_4'' , alongside two heavy fragments, labelled as A_1'' and A_2'' . These fragments can be systematically arranged in six distinct manners (see Fig. 5.4), aiming to comprehensively understand the fragmentation potential associated with each configuration. The resultant fragmentation potential is plotted and presented in Fig. 5.5. It's important to note that the colour scheme of the fragmentation potential in Fig. 5.5 corresponds to colour of each configuration depicted in Fig. 5.4. Analysing the fragmentation potential in Fig. 5.5, configuration(b) in Fig. 5.4 exhibits the lowest potential energy, indicating its higher probability of occurrence. This observation suggests that the formation of an elongated neck between two fragments seems to provide the favorable energetics. This may be due to the crucial influence of Coulombic forces between the fragments. Which tends to elongate the system, resulting in the formation of elongated neck. Also, the fragmentation potential of configuration (b) in Fig. 5.5 shows dominant minima in the fission region giving near symmetric fragments.

Further, to understand the behavior of quaternary fission, the fragmentation potential of the four body decay dynamics is studied. As previously discussed, the choice of A_3''

Table 5.1: The most preferred ternary ($A_1' + A_2' + A_3'$) and quaternary ($A_1'' + A_2'' + A_3'' + A_4''$) fission fragment combination along with fixed third and fourth fragment for ^{252}Cf . Respective atomic number (Z) and neutron number (N) are also listed.

Quaternary	Ternary	Quaternary	Ternary
$^{130}\text{Sn} + ^1\text{n} + ^1\text{n} + ^{120}\text{Cd}$ (50,80 + 0,1 + 0,1 + 48,72) $^{132}\text{Sn} + ^2\text{H} + ^2\text{H} + ^{116}\text{Pd}$ (50,82 + 1,1 + 1,1 + 46,70) $^{130}\text{Sn} + ^3\text{H} + ^3\text{H} + ^{116}\text{Pd}$ (50,80 + 1,2 + 1,2 + 46,70) $^{132}\text{Sn} + ^4\text{He} + ^4\text{He} + ^{112}\text{Ru}$ (50,82 + 2,2 + 2,2 + 44,68) $^{134}\text{Te} + ^5\text{He} + ^5\text{He} + ^{108}\text{Mo}$ (52,82 + 2,3 + 2,3 + 42,66) $^{134}\text{Te} + ^6\text{He} + ^6\text{He} + ^{106}\text{Mo}$ (52,82 + 2,4 + 2,4 + 42,64) $^{132}\text{Sn} + ^7\text{Li} + ^7\text{Li} + ^{106}\text{Mo}$ (50,82 + 3,4 + 3,4 + 42,64) $^{132}\text{Sn} + ^8\text{Be} + ^8\text{Be} + ^{104}\text{Zr}$ (50,82 + 4,4 + 4,4 + 40,64) $^{132}\text{Sn} + ^9\text{Be} + ^9\text{Be} + ^{102}\text{Zr}$ (50,82 + 4,5 + 4,5 + 40,62) $^{132}\text{Sn} + ^{10}\text{Be} + ^{10}\text{Be} + ^{100}\text{Zr}$ (50,82 + 4,6 + 4,6 + 40,60) $^{134}\text{Te} + ^{11}\text{Be} + ^{11}\text{Be} + ^{96}\text{Sr}$ (52,82 + 4,7 + 4,7 + 38,58) $^{134}\text{Te} + ^{12}\text{Be} + ^{12}\text{Be} + ^{94}\text{Sr}$ (52,82 + 4,8 + 4,8 + 38,56) $^{132}\text{Sn} + ^{13}\text{C} + ^{13}\text{C} + ^{94}\text{Kr}$ (50,82 + 6,7 + 6,7 + 36,58) $^{132}\text{Sn} + ^{14}\text{C} + ^{14}\text{C} + ^{92}\text{Kr}$ (50,82 + 6,8 + 6,8 + 36,56) $^{132}\text{Sn} + ^{15}\text{C} + ^{15}\text{C} + ^{90}\text{Kr}$ (50,82 + 6,9 + 6,9 + 36,54)	$^{130}\text{Sn} + ^1\text{n} + ^{121}\text{Cd}$ (50,80 + 0,1 + 48,73) $^{131}\text{Sn} + ^2\text{H} + ^{119}\text{Ag}$ (50,81 + 1,1 + 47,72) $^{133}\text{Sb} + ^3\text{H} + ^{116}\text{Pd}$ (51,82 + 1,2 + 46,70) $^{132}\text{Sn} + ^4\text{He} + ^{116}\text{Pd}$ (50,82 + 2,2 + 46,70) $^{131}\text{Sn} + ^5\text{He} + ^{116}\text{Pd}$ (50,81 + 2,3 + 46,70) $^{130}\text{Sn} + ^6\text{He} + ^{116}\text{Pd}$ (50,80 + 2,4 + 46,70) $^{133}\text{Sb} + ^7\text{Li} + ^{112}\text{Ru}$ (51,82 + 3,4 + 44,68) $^{132}\text{Sn} + ^8\text{Be} + ^{112}\text{Ru}$ (50,82 + 4,4 + 44,68) $^{131}\text{Sn} + ^9\text{Be} + ^{112}\text{Ru}$ (50,81 + 4,5 + 44,68) $^{134}\text{Te} + ^{10}\text{Be} + ^{108}\text{Mo}$ (52,82 + 4,6 + 42,66) $^{134}\text{Te} + ^{11}\text{Be} + ^{107}\text{Mo}$ (52,82 + 4,7 + 42,65) $^{134}\text{Te} + ^{12}\text{Be} + ^{106}\text{Mo}$ (52,82 + 4,8 + 42,64) $^{131}\text{Sn} + ^{13}\text{C} + ^{107}\text{Mo}$ (50,81 + 6,7 + 42,65) $^{132}\text{Sn} + ^{14}\text{C} + ^{106}\text{Mo}$ (50,82 + 6,8 + 42,64) $^{131}\text{Sn} + ^{15}\text{C} + ^{106}\text{Mo}$ (50,81 + 6,9 + 42,64)	$^{130}\text{Sn} + ^{21}\text{O} + ^{21}\text{O} + ^{80}\text{Ge}$ (50,80 + 8,13 + 8,13 + 32,48) $^{128}\text{Sn} + ^{22}\text{O} + ^{22}\text{O} + ^{80}\text{Ge}$ (50,78 + 8,14 + 8,14 + 32,48) $^{130}\text{Sn} + ^{23}\text{F} + ^{23}\text{F} + ^{76}\text{Zn}$ (50,80 + 9,14 + 9,14, 30,46) $^{132}\text{Sn} + ^{24}\text{Ne} + ^{24}\text{Ne} + ^{72}\text{Ni}$ (50,82 + 10,14 + 10,14 + 28,44) $^{132}\text{Sn} + ^{25}\text{Ne} + ^{25}\text{Ne} + ^{70}\text{Ni}$ (50,82 + 10,15 + 10,15 + 28,42) $^{130}\text{Sn} + ^{26}\text{Ne} + ^{26}\text{Ne} + ^{70}\text{Ni}$ (50,80 + 10,16 + 10,16 + 28,42) $^{132}\text{Sn} + ^{27}\text{Na} + ^{27}\text{Na} + ^{66}\text{Fe}$ (50,82 + 11,16 + 11,16 + 26,40) $^{132}\text{Sn} + ^{28}\text{Mg} + ^{28}\text{Mg} + ^{64}\text{Cr}$ (50,82 + 12,16 + 12,16 + 24,40) $^{132}\text{Sn} + ^{29}\text{Mg} + ^{29}\text{Mg} + ^{62}\text{Cr}$ (50,82 + 12,17 + 12,17 + 24,38) $^{132}\text{Sn} + ^{30}\text{Mg} + ^{30}\text{Mg} + ^{60}\text{Cr}$ (50,82 + 12,18 + 12,18 + 24,36) $^{132}\text{Sn} + ^{31}\text{Mg} + ^{31}\text{Mg} + ^{58}\text{Cr}$ (50,82 + 12,19 + 12,19 + 24,34) $^{130}\text{Sn} + ^{32}\text{Mg} + ^{32}\text{Mg} + ^{58}\text{Cr}$ (50,80 + 12,20 + 12,20 + 24,34) $^{132}\text{Sn} + ^{33}\text{Si} + ^{33}\text{Si} + ^{54}\text{Ca}$ (50,82 + 14,19 + 14,19 + 20,34) $^{132}\text{Sn} / ^{104}\text{Zr} + ^{34}\text{Si} + ^{34}\text{Si} + ^{52}\text{Ca} / ^{80}\text{Zn}$ (50,82 / 40,64 + 14,20 + 14,20 + 20,32 / 30,50) $^{132}\text{Sn} / ^{100}\text{Sr} + ^{35}\text{Si} + ^{35}\text{Si} + ^{50}\text{Ca} / ^{82}\text{Ge}$ (50,82 / 38,62 + 14,21 + 14,21 + 20,30 / 32,50)	$^{131}\text{Sb} + ^{21}\text{O} + ^{100}\text{Zr}$ (51,80 + 8,13 + 40,60) $^{134}\text{Te} + ^{22}\text{O} + ^{96}\text{Sr}$ (52,82 + 8,14 + 38,58) $^{133}\text{Sb} + ^{23}\text{F} + ^{96}\text{Sr}$ (51,82 + 9,14 + 38,58) $^{132}\text{Sn} + ^{24}\text{Ne} + ^{96}\text{Sr}$ (50,82 + 10,14 + 38,58) $^{131}\text{Sn} + ^{25}\text{Ne} + ^{96}\text{Sr}$ (50,81 + 10,15 + 38,58) $^{132}\text{Sn} + ^{26}\text{Ne} + ^{94}\text{Sr}$ (50,82 + 10,16 + 38,56) $^{133}\text{Sb} + ^{27}\text{Na} + ^{92}\text{Kr}$ (51,82 + 11,16 + 36,56) $^{132}\text{Sn} + ^{28}\text{Mg} + ^{92}\text{Kr}$ (50,82 + 12,16 + 36,56) $^{132}\text{Sn} + ^{29}\text{Mg} + ^{91}\text{Kr}$ (50,82 + 12,17 + 36,55) $^{132}\text{Sn} + ^{30}\text{Mg} + ^{90}\text{Kr}$ (50,82 + 12,18 + 36,54) $^{132}\text{Sn} + ^{31}\text{Mg} + ^{89}\text{Kr}$ (50,82 + 12,19 + 36,53) $^{134}\text{Te} + ^{32}\text{Mg} + ^{86}\text{Se}$ (52,82 + 12,20 + 34,52) $^{132}\text{Sn} + ^{33}\text{Si} + ^{87}\text{Se}$ (50,82 + 14,19 + 34,53) $^{132}\text{Sn} + ^{34}\text{Si} + ^{86}\text{Se}$ (50,82 + 14,20 + 34,52) $^{132}\text{Sn} + ^{35}\text{Si} + ^{85}\text{Se}$ (50,82 + 14,21 + 34,51)

5.2 Discussion

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Table 5.1 continued...

Quaternary	Ternary	Quaternary	Ternary
$^{134}\text{Te} + ^{16}\text{C} + ^{16}\text{C} + ^{86}\text{Se}$ (52,82 + 6,10 + 6,10 + 34,52) $^{132}\text{Sn} + ^{17}\text{N} + ^{17}\text{N} + ^{86}\text{Se}$ (50,82 + 7,10 + 7,10 + 34,52) $^{132}\text{Sn} + ^{18}\text{O} + ^{18}\text{O} + ^{84}\text{Ge}$ (50,82 + 8,10 + 8,10 + 32,52) $^{132}\text{Sn} + ^{19}\text{O} + ^{19}\text{O} + ^{82}\text{Ge}$ (50,82 + 8,11 + 8,11 + 32,50) $^{132}\text{Sn} + ^{20}\text{O} + ^{20}\text{O} + ^{80}\text{Ge}$ (50,82 + 8,12 + 8,12 + 32,48) $^{130}\text{Sn}/^{88}\text{Se} + ^{41}\text{S} + ^{41}\text{S} + ^{40}\text{S}/^{82}\text{Ge}$ (50,80/34,54 + 16,25 + 16,25 + 16,24/32,50) $^{130}\text{Sn}/^{86}\text{Se} + ^{42}\text{S} + ^{42}\text{S} + ^{38}\text{S}/^{82}\text{Ge}$ (50,80/34,52 + 16,26 + 16,26 + 16,22/32,50) $^{132}\text{Sn}/^{84}\text{Ge} + ^{43}\text{Cl} + ^{43}\text{Cl} + ^{34}\text{Si}/^{82}\text{Ge}$ (50,82/32,52 + 17,26 + 17,26 + 14,20/32,50) $^{132}\text{Sn}/^{84}\text{Ge} + ^{44}\text{Ar} + ^{44}\text{Ar} + ^{32}\text{Mg}/^{80}\text{Zn}$ (50,82/32,52 + 18,26 + 18,26 + 12,20/30,50) $^{132}\text{Sn}/^{82}\text{Ge} + ^{45}\text{Ar} + ^{45}\text{Ar} + ^{30}\text{Mg}/^{80}\text{Zn}$ (50,82/32,50 + 18,27 + 18,27 + 12,18/30,50) $^{132}\text{Sn}/^{82}\text{Ge} + ^{46}\text{Ar} + ^{46}\text{Ar} + ^{28}\text{Mg}/^{78}\text{Zn}$ (50,82/32,50 + 18,28 + 18,28 + 12,16/30,48) $^{132}\text{Sn}/^{80}\text{Zn} + ^{47}\text{K} + ^{47}\text{K} + ^{26}\text{Ne}/^{78}\text{Zn}$ (50,82/30,50 + 19,28 + 19,28 + 10,16/30,48) $^{134}\text{Sn}/^{80}\text{Zn} + ^{48}\text{Ca} + ^{48}\text{Ca} + ^{22}\text{O}/^{76}\text{Ni}$ (50,84/30,50 + 20,28 + 20,28 + 8,14/28,48) $^{132}\text{Sn}/^{80}\text{Zn} + ^{49}\text{Ca} + ^{49}\text{Ca} + ^{22}\text{O}/^{74}\text{Ni}$ (50,82/30,50 + 20,29 + 20,29 + 8,14/28,46) $^{132}\text{Sn}/^{78}\text{Zn} + ^{50}\text{Ca} + ^{50}\text{Ca} + ^{20}\text{O}/^{74}\text{Ni}$ (50,82/30,48 + 20,30 + 20,30 + 8,12/28,46)	$^{134}\text{Te} + ^{16}\text{C} + ^{102}\text{Zr}$ (52,82 + 6,10 + 40,62) $^{133}\text{Sb} + ^{17}\text{N} + ^{102}\text{Zr}$ (51,82 + 7,10 + 40,62) $^{132}\text{Sn} + ^{18}\text{O} + ^{102}\text{Zr}$ (50,82 + 8,10 + 40,62) $^{132}\text{Sn} + ^{19}\text{O} + ^{101}\text{Zr}$ (50,82 + 8,11 + 40,61) $^{132}\text{Sn} + ^{20}\text{O} + ^{100}\text{Zr}$ (50,82 + 8,12 + 40,60) $^{131}\text{Sn} + ^{41}\text{S} + ^{80}\text{Ge}$ (50,81 + 16,25 + 32,48) $^{130}\text{Sn} + ^{42}\text{S} + ^{80}\text{Ge}$ (50,80 + 16,26 + 32,48) $^{133}\text{Sb} + ^{43}\text{Cl} + ^{76}\text{Zn}$ (51,82 + 17,26 + 30,46) $^{132}\text{Sn} + ^{44}\text{Ar} + ^{76}\text{Zn}$ (50,82 + 18,26 + 30,46) $^{131}\text{Sn} + ^{45}\text{Ar} + ^{76}\text{Zn}$ (50,81 + 18,17 + 30,46) $^{130}\text{Sn} + ^{46}\text{Ar} + ^{76}\text{Zn}$ (50,80 + 18,28 + 30,46) $^{133}\text{Sb} + ^{47}\text{K} + ^{72}\text{Ni}$ (51,82 + 19,28 + 28,44) $^{132}\text{Sn} + ^{48}\text{Ca} + ^{72}\text{Ni}$ (50,82 + 20,28 + 28,44) $^{131}\text{Sn} + ^{49}\text{Ca} + ^{72}\text{Ni}$ (50,81 + 20,29 + 28,44) $^{132}\text{Sn} + ^{50}\text{Ca} + ^{70}\text{Ni}$ (50,82 + 20,30 + 28,42)	$^{132}\text{Sn}/^{98}\text{Sr} + ^{36}\text{Si} + ^{36}\text{Si} + ^{48}\text{Ca}/^{82}\text{Ge}$ (50,82/38,60 + 14,22 + 14,22 + 20,28/32,50) $^{132}\text{Sn}/^{98}\text{Sr} + ^{37}\text{P} + ^{46}\text{Ar}/^{80}\text{Zn}$ (50,82/38,60 + 15,22 + 15,22 + 18,30/30,50) $^{130}\text{Sn}/^{88}\text{Se} + ^{38}\text{S} + ^{40}\text{S}/^{82}\text{Ge}$ (50,82/34,54 + 16,22 + 16,22 + 16,24/32,50) $^{132}\text{Sn}/^{94}\text{Kr} + ^{39}\text{S} + ^{42}\text{S}/^{80}\text{Zn}$ (50,82/36 + 16,23 + 16,23 + 16,26/30,50) $^{132}\text{Sn}/^{88}\text{Se} + ^{40}\text{S} + ^{40}\text{S}/^{84}\text{Ge}$ (50,82/34,54 + 16,24 + 16,24 + 16,24/32,52)	$^{132}\text{Sn} + ^{36}\text{Si} + ^{84}\text{Se}$ (50,82 + 14,22 + 34,50) $^{133}\text{Sb} + ^{37}\text{P} + ^{82}\text{Ge}$ (51,82 + 15,22 + 32,50) $^{132}\text{Sn} + ^{38}\text{S} + ^{82}\text{Ge}$ (50,82 + 16,22 + 32,50) $^{131}\text{Sn} + ^{39}\text{S} + ^{82}\text{Ge}$ (50,81 + 16,23 + 32,50) $^{130}\text{Sn} + ^{40}\text{S} + ^{82}\text{Ge}$ (50,80 + 16,24 32,50) $^{132}\text{Sn}/^{110}\text{Mo} + ^{64}\text{Fe} + ^{56}\text{Ti}/^{78}\text{Zn}$ (50,82/42,68 + 26,38 + 22,34/30,48) $^{132}\text{Sn}/^{105}\text{Zr} + ^{65}\text{Fe} + ^{55}\text{Ti}/^{82}\text{Ge}$ (50,82/40,65 + 26,39 + 22,33/32,50) $^{132}\text{Sn}/^{104}\text{Zr} + ^{66}\text{Fe} + ^{54}\text{Ti}/^{82}\text{Ge}$ (50,82/40,64 + 26,40 + 22,32/32,50) $^{131}\text{Sn}/^{103}\text{Zr} + ^{67}\text{Fe} + ^{54}\text{Ti}/^{82}\text{Ge}$ (50,81/40,63 + 26,41 + 22,32/32,50) $^{134}\text{Te}/^{102}\text{Zr} + ^{68}\text{Fe} + ^{50}\text{Ca}/^{82}\text{Ge}$ (52,82/40,62 + 26,42 + 20,30/32,50) $^{133}\text{Sb}/^{101}\text{Y} + ^{69}\text{Co} + ^{50}\text{Ca}/^{82}\text{Ge}$ (51,82/39,62 + 27,42 + 20,30/32,50) $^{132}\text{Sn}/^{102}\text{Zr} + ^{70}\text{Ni} + ^{50}\text{Ca}/^{80}\text{Zn}$ (50,82/40,62 + 28,42 + 20,30/30,50) $^{132}\text{Sn}/^{99}\text{Sr} + ^{71}\text{Ni} + ^{49}\text{Ca}/^{82}\text{Ge}$ (50,82/38,61 + 28,43 + 20,29/32,50) $^{132}\text{Sn}/^{98}\text{Sr} + ^{72}\text{Ni} + ^{48}\text{Ca}/^{82}\text{Ge}$ (50,82/38,60 + 28,44 + 20,28/32,50) $^{131}\text{Sn}/^{97}\text{Sr} + ^{73}\text{Ni} + ^{48}\text{Ca}/^{82}\text{Ge}$ (50,81/38,59 + 28,45 + 20,28/32,50)

Table 5.1 continued...

Quaternary	Ternary	Quaternary	Ternary
$^{136}\text{Te}/^{78}\text{Zn} + ^{51}\text{Ca} + ^{14}\text{C}/^{72}\text{Ni}$ (52,84/30,48 + 20,31 + 20,31 + 6,8/28,44)	$^{131}\text{Sn} + ^{51}\text{Ca} + ^{70}\text{Ni}$ (50,81 + 20,31 + 28,42)	$^{130}\text{Sn}/^{96}\text{Sr} + ^{74}\text{Ni} + ^{48}\text{Ca}/^{82}\text{Ge}$ (50,80/38,58 + 28,46 + 20,28/32,50)	
$^{134}\text{Te}/^{78}\text{Zn} + ^{52}\text{Ca} + ^{14}\text{C}/^{70}\text{Ni}$ (52,82/30,48 + 20,32 + 20,32 + 6,8/28,42)	$^{130}\text{Sn} + ^{52}\text{Ca} + ^{70}\text{Ni}$ (50,80 + 20,32 + 28,42)	$^{130}\text{Sn}/^{95}\text{Rb} + ^{75}\text{Cu} + ^{47}\text{K}/^{82}\text{Ge}$ (50,80/37,58 + 29,46 + 19,28/32,50)	
$^{132}\text{Sn}/^{74}\text{Ni} + ^{53}\text{Sc} + ^{14}\text{C}/^{72}\text{Ni}$ (50,82/28,46 + 21,32 + 21,32 + 6,8/28,44)	$^{133}\text{Sb} + ^{53}\text{Sc} + ^{66}\text{Fe}$ (51,82 + 21,32 + 26,40)	$^{130}\text{Sn}/^{98}\text{Sr} + ^{76}\text{Zn} + ^{46}\text{Ar}/^{78}\text{Zn}$ (50,80/38,60 + 30,46 + 18,28/30,48)	
$^{140}\text{Te}/^{76}\text{Ni} + ^{54}\text{Ti} + ^{4}\text{He}/^{68}\text{Fe}$ (52,88/28,48 + 22,32 + 22,32 + 2,2/26,42)	$^{132}\text{Sn} + ^{54}\text{Ti} + ^{66}\text{Fe}$ (50,82 + 22,32 + 26,40)	$^{131}\text{Sn}/^{97}\text{Sr} + ^{77}\text{Zn} + ^{44}\text{Ar}/^{78}\text{Zn}$ (50,81/38,59 + 30,47 + 18,26/30,48)	
$^{138}\text{Te}/^{74}\text{Ni} + ^{55}\text{Ti} + ^{4}\text{He}/^{68}\text{Fe}$ (52,86/28,46 + 22,33 + 22,33 + 2,2/26,42)	$^{132}\text{Sn} + ^{55}\text{Ti} + ^{66}\text{Fe}$ (50,82 + 22,33 + 26,40)	$^{130}\text{Sn}/^{92}\text{Kr} + ^{78}\text{Zn} + ^{44}\text{Ar}/^{82}\text{Ge}$ (50,80/36,56 + 30,48 + 18,26/32,50)	
$^{136}\text{Te}/^{80}\text{Zn} + ^{56}\text{Ti} + ^{56}\text{Ti} + ^{4}\text{He}/^{60}\text{Cr}$ (52,84/30,50 + 22,34 + 22,34 + 2,2/24,36)	$^{132}\text{Sn} + ^{56}\text{Ti} + ^{64}\text{Fe}$ (50,82 + 22,34 + 26,38)	$^{129}\text{Sn}/^{87}\text{Se} + ^{79}\text{Zn} + ^{44}\text{Ar}/^{86}\text{Se}$ (50,79/34,53 + 30,49 + 18,26/34,52)	
$^{134}\text{Te}/^{78}\text{Zn} + ^{57}\text{Ti} + ^{57}\text{Ti} + ^{4}\text{He}/^{60}\text{Cr}$ (52,82/30,48 + 22,35 + 22,35 + 2,2/24,36)	$^{131}\text{Sn} + ^{57}\text{Ti} + ^{64}\text{Fe}$ (50,81 + 22,35 + 26,38)	$^{132}\text{Sn}/^{92}\text{Kr} + ^{80}\text{Ge} + ^{40}\text{S}/^{80}\text{Zn}$ (50,82/36,56 + 32,48 + 16,24/30,50)	
$^{132}\text{Te}/^{82}\text{Ge} + ^{58}\text{Ti} + ^{58}\text{Ti} + ^{4}\text{He}/^{54}\text{Ti}$ (52,80/32,50 + 22,36 + 22,36 + 2,2/22,32)	$^{130}\text{Sn} + ^{58}\text{Ti} + ^{64}\text{Fe}$ (50,80 + 22,36 + 26,38)	$^{131}\text{Sn}/^{86}\text{Se} + ^{81}\text{Ga} + ^{40}\text{S}/^{85}\text{As}$ (50,81/34,52 + 31,50 + 16,24/33,52)	
$^{130}\text{Sn}/^{82}\text{Ge} + ^{59}\text{V} + ^{59}\text{V} + ^{4}\text{He}/^{52}\text{Ca}$ (50,80/32,50 + 23,36 + 23,36 + 2,2/20,32)	$^{133}\text{Sb} + ^{59}\text{V} + ^{60}\text{Cr}$ (51,82 + 23,36 + 24,36)	$^{130}\text{Sn}/^{88}\text{Se} + ^{82}\text{Ge} + ^{40}\text{S}/^{82}\text{Ge}$ (50,80/34,54 + 32,50 + 16,24/32,50)	
$^{128}\text{Cd}/^{80}\text{Zn} + ^{60}\text{Cr} + ^{60}\text{Cr} + ^{4}\text{He}/^{52}\text{Ca}$ (48,80/30,50 + 24,36 + 24,36 + 2,2/20,32)	$^{132}\text{Sn} + ^{60}\text{Cr} + ^{60}\text{Cr}$ (50,82 + 24,36 + 24,36)	$^{129}\text{Sn}/^{86}\text{Se} + ^{83}\text{Ge} + ^{40}\text{S}/^{83}\text{Ge}$ (50,79/34,52 + 32,51 + 16,24/32,51)	
$^{126}\text{Cd}/^{80}\text{Zn} + ^{61}\text{Cr} + ^{61}\text{Cr} + ^{4}\text{He}/^{50}\text{Ca}$ (48,78/30,50 + 24,37 + 24,37 + 2,2/20,30)	$^{131}\text{Sn} + ^{61}\text{Cr} + ^{60}\text{Cr}$ (50,81 + 24,37 + 24,36)	$^{130}\text{Sn}/^{84}\text{Ge} + ^{84}\text{Se} + ^{36}\text{Si}/^{84}\text{Ge}$ (50,80/32,52 + 34,50 + 14,22/32,52)	
$^{124}\text{Cd}/^{78}\text{Zn} + ^{62}\text{Cr} + ^{62}\text{Cr} + ^{4}\text{He}/^{50}\text{Ca}$ (48,76/30,48 + 24,38 + 24,38 + 2,2/20,30)	$^{132}\text{Sn} + ^{62}\text{Cr} + ^{58}\text{Cr}$ (50,82 + 24,38 + 24,34)		
$^{122}\text{Pd}/^{80}\text{Zn} + ^{63}\text{Mn} + ^{63}\text{Mn} + ^{4}\text{He}/^{46}\text{Ar}$ (46,76/30,50 + 25,38 + 25,38 + 2,2/18,28)	$^{133}\text{Sb} + ^{63}\text{Mn} + ^{56}\text{Ti}$ (51,82 + 25,38 + 22,34)		

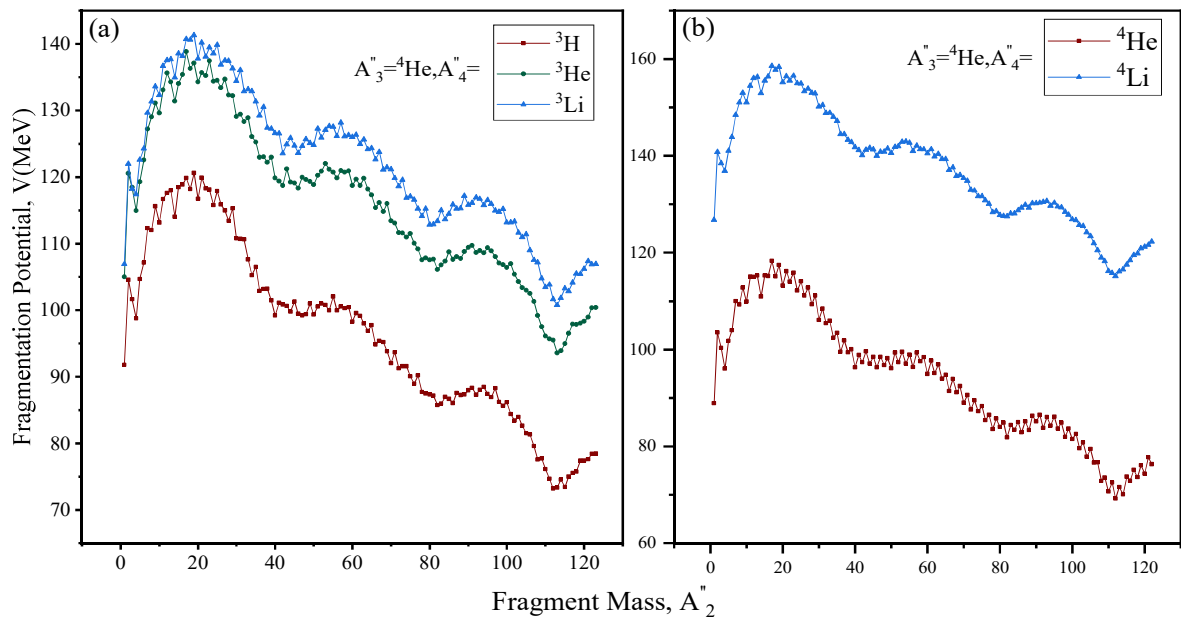
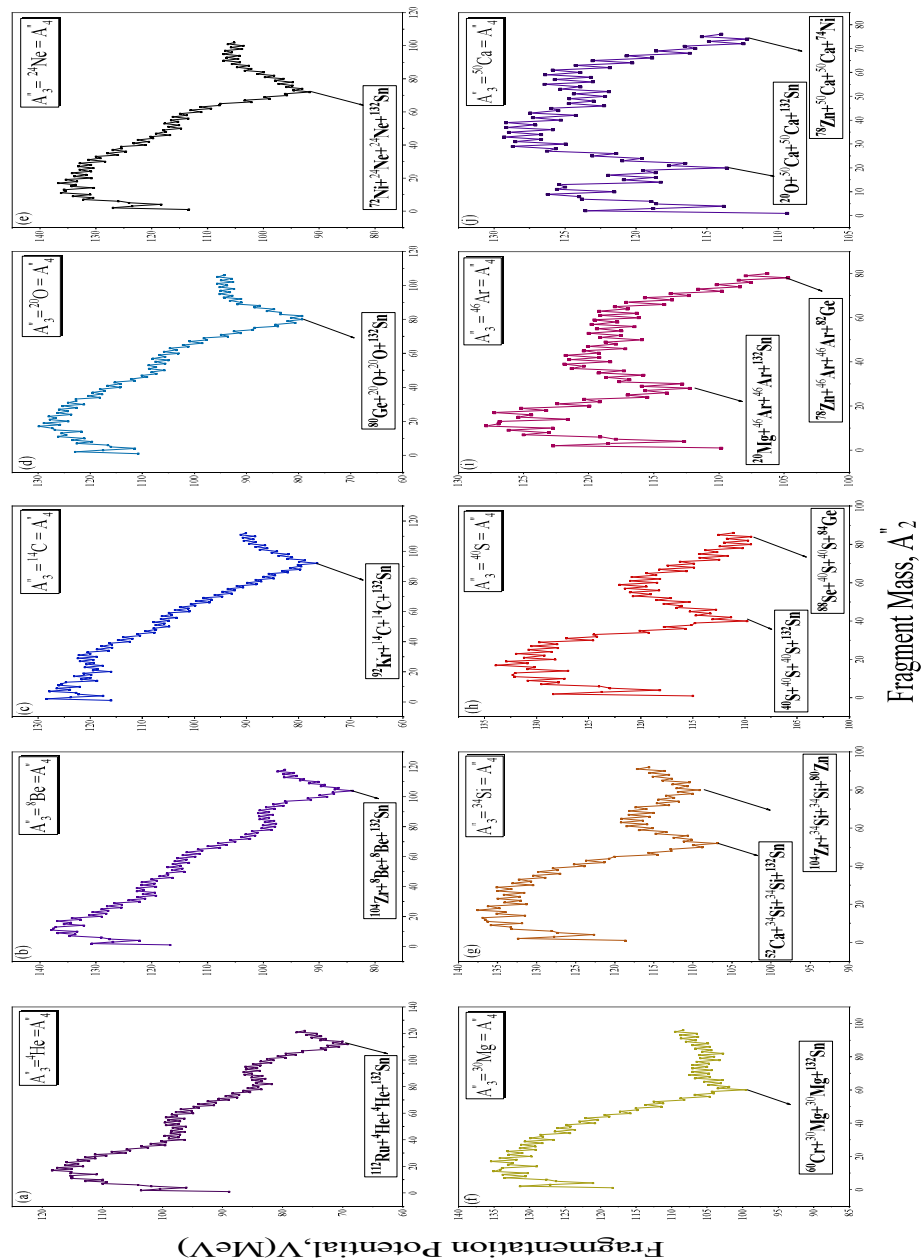


Figure 5.6: Quaternary fragmentation potential for collinear emission of fragments in four body decay of ^{252}Cf nucleus for different fragments with mass number $A_4''=3$ with fixed $A_3''={}^4\text{He}$ plotted as a function of mass number A_2''

as ${}^4\text{He}$ holds considerable significance. Therefore, choice of A_3'' remain fixed. Note that the choice of fourth fragment is made by taking mass number of A_4'' as 3 and 4. For fragment mass number 3, three possibilities such as ${}^3\text{H}$, ${}^3\text{He}$, ${}^3\text{Li}$ are taken, leaving the remaining system as ${}^{246}\text{Am}$, ${}^{246}\text{Pu}$ and ${}^{246}\text{Np}$, respectively. The quaternary fragmentation potential is plotted by taking these choices for ^{252}Cf nucleus and shown in Fig. 5.6(a). It's evident from the figure that the magnitude of the quaternary fragmentation potential is lower for $A_4'' = {}^3\text{H}$ compared to ${}^3\text{He}$ and ${}^3\text{Li}$ fragments. Therefore (A_1, α, t, A_2) is more probable option in the quaternary decay of ^{252}Cf . Similarly, $A_4 = 4$, with the possible choices for mass number 4 being ${}^4\text{He}$ and ${}^4\text{Li}$. The corresponding fragmentation potential is plotted in Fig. 5.6(b). As the magnitude of the fragmentation potential is lowest for $A_4 = {}^4\text{He}$, it suggests that $(A_1, \alpha, \alpha, A_2)$ are the preferred decaying fragments in quaternary fission. This preference for $(A_1, \alpha, \alpha, A_2)$ and (A_1, α, t, A_2) particles in quaternary fission, aligns with the experimental observations [?]. This preference may be attributed to several factors. The fragmentation potential includes binding energy, Coulomb potential, and proximity potential, all of which play important role. As the mass number is same

Figure 5.7: Fragmentation potential of quaternary fission of ^{252}Cf with respect to mass number A'_2 for $A'_3 = A'_4 =$ (a) ^4He (b) ^8Be (c) ^{14}C (d) ^{20}O (e) ^{26}Ne (f) ^{30}Mg (g) ^{34}Si (h) ^{40}S (i) ^{46}Ar (j) ^{50}Ca



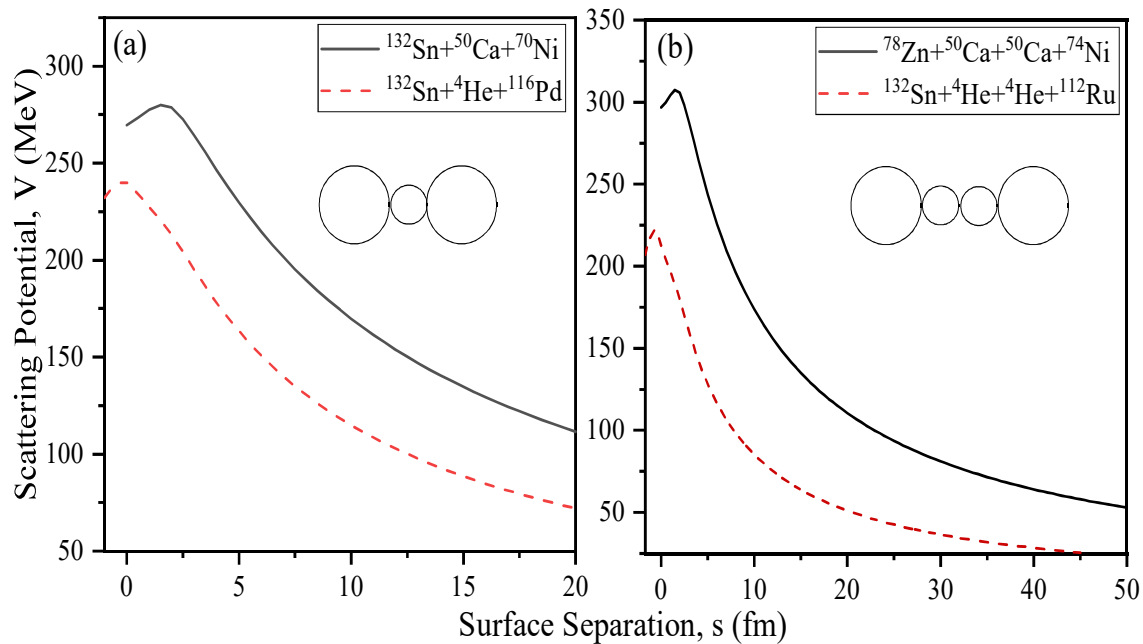


Figure 5.8: Scattering potential V (MeV) as function of surface separation distance (s) for (a) ternary fission by taking fixed third fragment such as $A_3 = ^4\text{He}$ and ^{50}Ca (b) quaternary fission by taking fixed third and fourth fragment such as $A_3 = A_4 = ^4\text{He}$ and ^{50}Ca

therefore, charges of the emitted fragments play crucial role, modifying the fragmentation process. Understanding these factors is essential for comprehending the complex phenomena governing quaternary fission of heavy nuclei. Interestingly, the structural analysis of Fig. 5.6(a) and (b) shows that the minima lies in the fission region. To understand these minima in the fission region, different choices of ($A_3'' = A_4''$) middle fragments are chosen such as ^4He , ^8Be , ^{14}C , ^{20}O , ^{24}Ne , ^{30}Mg , ^{34}Si , ^{40}S , ^{46}Ar and ^{50}Ca . The fragmentation potential for these combinations is plotted in Fig. 5.7(a)-5.7(j). The aim is to analyse the fragmentation potential across a range of lighter to heavier middle fragments. From Fig. 5.7(a)-(f), the most probable fragment combinations have been identified as follows: ^{112}Ru ($N=68, Z=44$) + ^{132}Sn ($N=82, Z=50$), ^{104}Zr ($N=64, Z=40$) + ^{132}Sn ($N=82, Z=50$), ^{92}Kr ($N=56, Z=36$) + ^{132}Sn ($N=82, Z=50$), ^{80}Ge ($N=48, Z=32$) + ^{132}Sn ($N=82, Z=50$), ^{72}Ni ($N=44, Z=28$) + ^{132}Sn ($N=82, Z=50$), ^{60}Cr ($N=36, Z=24$) + ^{132}Sn ($N=50, Z=82$), respectively for $A_3''=A_4'' = ^4\text{He}$, ^8Be , ^{14}C , ^{20}O , ^{24}Ne and ^{30}Mg . This observation could be attributed to the presence of shell closure as one of the identified fission fragments exhibit either proton or neutron magicity. The neutron and proton magic numbers are

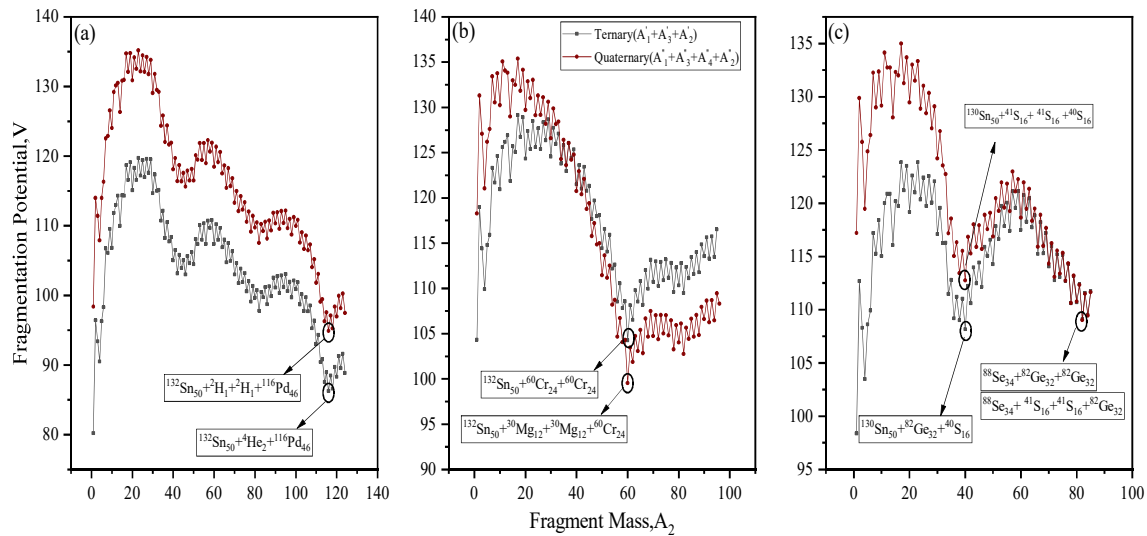


Figure 5.9: Comparison of ternary ($A'_1 + A'_2 + A'_3$) and quaternary ($A''_1 + A''_2 + A''_3 + A''_4$) fission fragmentation with respect to mass number A_2 or A_2'' (a) $A'_3 = {}^4\text{He}$, $A''_3 = A''_4 = {}^2\text{H}$ (b) $A'_3 = {}^{60}\text{Cr}$, $A''_3 = A''_4 = {}^{30}\text{Mg}$ (c) $A'_3 = {}^{82}\text{Ge}$, $A''_3 = A''_4 = {}^{41}\text{S}$

marked with bold letters. Interestingly, for heavier middle fragments ($A''_3 = A''_4$) two dips emerges in the fragmentation potential. Which are mentioned in Fig. 5.7(g)-5.7(j). A notable observation is that for $A''_3 = A''_4 = {}^{34}\text{Si}$ and ${}^{40}\text{S}$, the most probable fragments are ${}^{52}\text{Ca}$ ($N=32, Z=20$)+ ${}^{132}\text{Sn}$ ($N=50, Z=82$) and ${}^{40}\text{S}$ ($N=24, Z=16$)+ ${}^{132}\text{Sn}$ ($N=50, Z=82$) with the secondary dip at ${}^{104}\text{Zr}$ ($N=64, Z=40$)+ ${}^{80}\text{Zn}$ ($N=50, Z=30$) and ${}^{88}\text{Se}$ ($N=54, Z=34$)+ ${}^{84}\text{Ge}$ ($N=52, Z=32$), respectively. Whereas, for fragments $A''_3 = A''_4 = {}^{46}\text{Ar}$ and ${}^{50}\text{Ca}$ the most probable fragments are ${}^{78}\text{Ru}$ ($N=48, Z=30$)+ ${}^{82}\text{Ge}$ ($N=50, Z=32$) and ${}^{78}\text{Zn}$ ($N=48, Z=30$)+ ${}^{72}\text{Ni}$ ($N=44, Z=28$) with secondary dip at ${}^{20}\text{Mg}$ ($N=8, Z=12$)+ ${}^{132}\text{Sn}$ ($N=50, Z=82$) and ${}^{20}\text{O}$ ($N=12, Z=8$)+ ${}^{132}\text{Sn}$ ($N=50, Z=82$) respectively. In addition to this, one can clearly see from Fig. 5.7, that the quaternary fragmentation potential has lower magnitude for $A''_3 = A''_4 = {}^4\text{He}$ case.

To elucidate the analogous behavior exhibited by heavy particles in ternary and quaternary fission of ${}^{252}\text{Cf}$, the most preferred choices of $A''_3 = A''_4$ ranging from 1 to $A_p/4$ are worked out. Note that the condition $A''_1 \geq A''_2 \geq A''_3 \geq A''_4$ is imposed to avoid the repetition of the fragment combination. The combination ($A''_1 + A''_2 + A''_3 + A''_4$) having the lowest value for quaternary fragmentation for all possible cases is shown in Table 5.1. A notable observation is that while moving from lighter to heavier middle fragments,

another dip emerge in the fragmentation potential. The corresponding proton and neutron numbers are also indicated beneath each fragment combination as $(Z_1, N_1 + Z_3, N_3 + Z_4, N_4 + Z_2, N_2)$. The neutron and proton shell closures of the fragments are indicated in bold. Similarly the possibility of ternary fission of ^{252}Cf is explored. All preferred third fragment ($A'_3 = 1$ to $A_p/3$) for ternary fission was also identified with condition $A'_1 \geq A'_2 \geq A'_3$ and shown in 2nd and 4th column of Table 5.1. The choice of third fragment A_3 remains same for the different decay modes i.e. ternary (A'_3) and quaternary ($A''_3 = A''_4$) fission of ^{252}Cf . However, the most preferred $A_1 + A_2$ combinations get changed and are listed in Table 5.1. The Table 5.1 shows that as the mass of the middle fragment increases, a second dip starts emerging in the fragmentation potential. For quaternary fission of ^{252}Cf it starts at $A''_3 = A''_4 = ^{34}\text{Si}$ and for ternary fission it starts from $A'_3 = ^{64}\text{Fe}$. The secondary dip is also mentioned in the Table 5.1. This secondary dip emerges for ternary fission when mass of the third fragment is 25% of the parent nucleus. Interestingly, for quaternary fission the secondary dip emerges when the mass of the third or forth fragment is 13%. This is due to the fact that shell closure start playing its role for such fragments. It is important to note that, with few exceptions, the identified fragment combinations correspond to nuclei exhibiting shell closures. This result is in agreement with references [? ?]. Interestingly, several of the predicted third fragments listed in Table 5.1 correspond to fragments/clusters that have either been experimentally observed or theoretically predicted in cluster radioactivity (CR) (^{14}C , ^{24}Ne , ^{28}Mg , ^{30}Mg , ^{46}Ar , ^{48}Ca , ^{50}Ca) or in the induced ternary fission process [? ? ? ?].

The magnitude of the fragmentation potential increases as the masses of the two middle fragments (A''_3 and A''_4). Therefore, it can be concluded that the emission of the lightest particle is the most favorable. However for heavier A''_3 and A''_4 , the complementary fragments starts competing with the lighter ones. Therefore, one can conclude that α -particle is the most probable decay mode in binary, ternary and quaternary decay of ^{252}Cf nucleus.

Experimentally ternary fission of ^{252}Cf nucleus along the fission axis was observed by Pyatkov *et al.* [? ? ?], by employing the missing-mass method and reported $^{48-56}\text{Ca}$

as third fragment accompanied by $^{68-74}\text{Ni}$ and $^{129-133}\text{Sn}$ in the ternary fission of ^{252}Cf . The remaining fragments are stabilized via $Z=50$ and $N=82$ shell closures, as highlighted in Table 5.1. Our theoretical observations are in good agreement with the experimental data. Additionally, evidence for quaternary fission has been indicated in experimental observations by Pyatkov *et al.* [? ? ?], showing that the fission fragments include $Z = 28, 34$. These nuclei are also identified and listed in Table 5.1. The isotopes ^{34}Si , ^{46}Ar , and $^{48-52}\text{Ca}$ are identified as the third and fourth ($A_3'' = A_4''$) fragments in the quaternary fission of ^{252}Cf . One of the complementary fragments is found to be $^{130-132}\text{Sn}$. The significance of these fragments is attributed to the shell closure effects (also listed in Table 5.1). The above observations hold potential for future studies and may serve as important reference point for the future investigations.

After the identification of the most probable decay channels, the barrier characteristics are studied by calculating scattering potential. Fig. 5.8(a)-(b) illustrates the scattering potential, calculated using the relation $V=V_{Cij} + V_{Pij}$, as a function of the separation distance (s) for two selected combinations of the third and fourth fragments. While Table 5.1 provides several possible combinations, this specific analysis focuses on understanding the behavior of lighter and heavier fragments. For this purpose, $A_3 = ^4\text{He}$ and ^{50}Ca are chosen. Moreover, there is experimental evidence showing the detection of particles like ^4He and ^{50}Ca in both ternary and binary fission of the ^{252}Cf nucleus. The scattering potential represents the interaction between the fragments as a function of the surface separation s , as described in Eq. 2.48, specifically for the quaternary decay. This approach allows for a systematic examination of the impact of potential and the surface-separation on the barrier characteristics, for different choices of third and fourth fragments in the ternary and quaternary fission processes

In the present calculations, the surface separation for the heavier third (A_3') and the fourth fragment ($A_3'' = A_4''$), corresponding to ^{50}Ca in the ternary and quaternary fission of ^{252}Cf , is considered at the touching configuration ($s = 0$). For the lighter third fragment, specifically $A_3' = ^4\text{He}$, the surface separation is set at $s = -1.0$ fm. Similarly for the quaternary fission for the lighter third and forth fragment i.e. $A_3'' = A_4'' = ^4\text{He}$ surface separation is taken to be $s = -1.7$ fm. This choice of surface separation ensures that the barrier penetration

point is less than the barrier height, so that the tunneling criteria is fulfilled. The barrier height for $A_3 = {}^4\text{He}$ is lower than $A_3 = {}^{50}\text{Ca}$ (see Fig. 5.2(a)) for the ternary fission of ${}^{252}\text{Cf}$. Similarly for the quaternary fission, the barrier height is lower for $A_3'' = A_4'' = {}^4\text{He}$ than ${}^{50}\text{Ca}$. Notably, the lower barrier height observed for α -decay implies that it is a more probable decay mode compared to paths with higher barrier heights, where the probability of decay decreases accordingly. This trend underscores a greater likelihood of decay involving lighter fragments than the heavier ones. Consequently, the scattering potential results align well with those obtained from the fragmentation potential analysis, affirming that α -decay remains the most probable decay mode in the ternary and quaternary decay of ${}^{252}\text{Cf}$.

The Table. 5.1 indicate that for $A_3'' = A_4'' = {}^2\text{H}$ and $A_3' = {}^4\text{He}$, the complementary fragments are same (see Table 5.1) i.e. ${}^{132}\text{Sn} + {}^{116}\text{Pd}$. There are other cases as well in which the complementary fragments are same for ternary and quaternary fission. To understand this behaviour a comparative analysis is done for the different choices of middle fragments giving rise to same complementary fragments as shown in Fig. 5.9. The choices are $A_3' = {}^4\text{He}$, ${}^{60}\text{Cr}$, ${}^{82}\text{Ge}$ and $A_3'' = A_4'' = {}^2\text{H}$, ${}^{30}\text{Mg}$, ${}^{41}\text{S}$ along with same complementary fragments ${}^{132}\text{Sn} + {}^{116}\text{Pd}$, ${}^{132}\text{Sn} + {}^{60}\text{Cr}$, ${}^{130}\text{Sn} + {}^{40}\text{S}$, respectively.

Despite the interactions between fragments are different for ternary and quaternary fission, the complementary fragments remain the same, with the differences manifesting in the magnitude of the fragmentation potentials (see Fig. 5.9). The comparative analysis indicates that the magnitude of fragmentation potential, influenced by binding energy, Coulomb potential, and proximity potential, varies significantly when shifting from ternary to quaternary fission (seen in eqn. 2.28, 2.38). Additionally, as the mass of the third and fourth fragments increases, ternary and quaternary fission begin to compete with each other. The analysis, illustrated in Fig. 5.9, shows significant variations when transitioning from ternary to quaternary fission. Specifically, the proximity potential can vary up to 23%, the Coulomb potential by up to 9%, and the binding energy by 25%. These variations account for the observed dips in the fragmentation potential, reflecting the complex dynamics that determine the stability and formation of the fission fragments. Which describes the dip in the fragmentation potential. Further, to understand the role of

surface separation (s), a detailed analysis of relative yield is explored in the next section.

5.2.3 Role of surface separation (s) in the multicluster emission of ^{252}Cf

In this section, ternary and quaternary fission modes are explored. As the difference between the barrier height (V_B) and the Q -value serves an alternative method for estimating the decay probability. $V_B - Q$ values for ternary and quaternary fission while keeping $A_3 = {}^{50}\text{Ca}$ and $A_3 = A_4 = {}^{50}\text{Ca}$ as fixed fragments, are shown in Fig. 5.10. It is evident from the figure that the structural pattern of this figure closely follows the fragmentation potential discussed later in Fig. 5.12.

Additionally, the penetration probability is calculated using the barrier characteristics, which can be further employed to calculate the relative yield [?].

The surface separation (s) between fragments plays a crucial role in the decay process and the relative yield of the fragments. Considering this, the barrier penetrability and relative yield have been calculated, with $A_3 = {}^{50}\text{Ca}$ for ternary fission (experimentally observed candidate [?]), and $A_3 = A_4 = {}^{50}\text{Ca}$ for quaternary fission with surface separation range of $s=0$ and $s=1$ fm. The fragmentation potential and relative yield are found to increase with increase in the magnitude of surface separation (s). Fig. 5.11 illustrates the relative yield for both ternary and quaternary fission at surface separations $s=0$ fm and $s=1$ fm. The overall distribution is asymmetric for the ternary decay, whereas the same is symmetric for the quaternary channel. Besides studying the role of the surface separation in barrier penetrability and relative yield, the fragmentation structure at $s=0$ fm and $s=1$ fm is shown in Fig. 5.12. The results indicate that the overall fragmentation structure remains unchanged for both surface separations, suggesting that the choice of the most probable fragment is independent of the choice of surface separation.

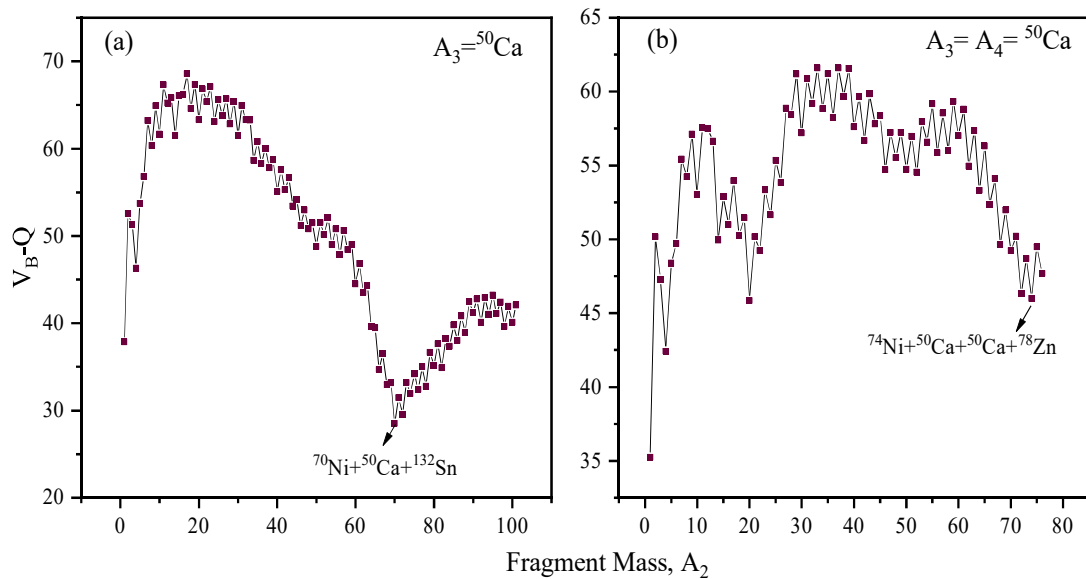


Figure 5.10: Calculated V_B-Q with respect to fragment mass A_2 by considering (a) for ternary $A_3 = ^{50}\text{Ca}$ and (b) quaternary $A_3 = A_4 = ^{50}\text{Ca}$

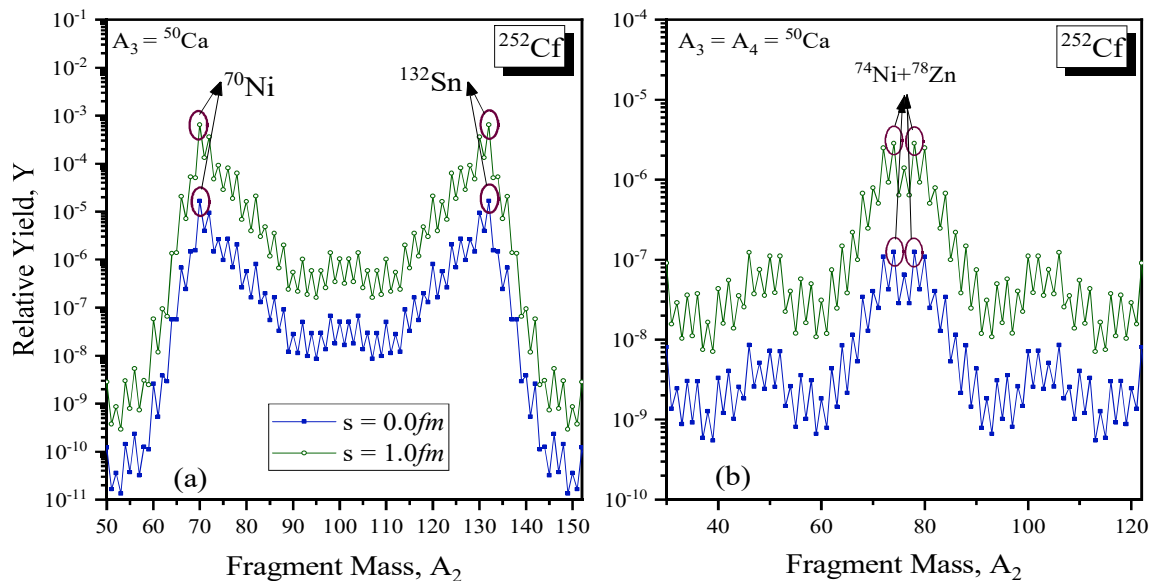


Figure 5.11: Relative yield of ^{252}Cf with respect to fragment mass A_2 (a) for ternary (taking $A_3 = ^{50}\text{Ca}$) and (b) quaternary (taking $A_3 = A_4 = ^{50}\text{Ca}$) fission.

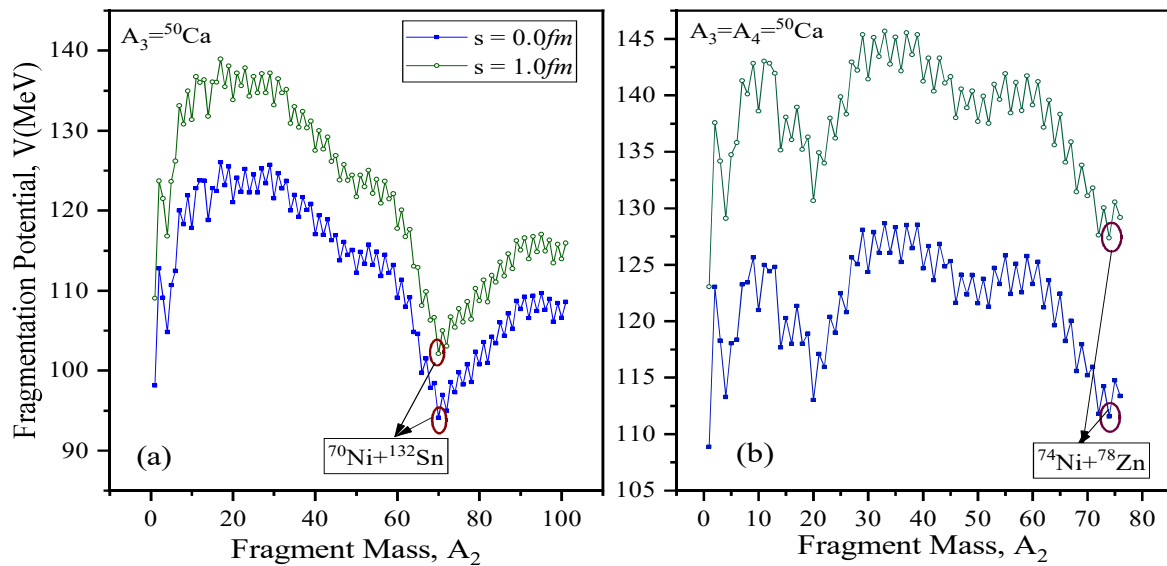


Figure 5.12: Fragmentation potential of ^{252}Cf with respect to fragment mass A_2 (a) for ternary (taking $A_3 = ^{50}\text{Ca}$) and (b) quaternary (taking $A_3 = A_4 = ^{50}\text{Ca}$) fission.

5.2.4 Multicluster emission from ^{252}Cf by considering different combinations of middle fragments with equatorial and collinear configurations

Quaternary fission

In order to comprehend the quaternary fission of the radioactive nucleus ^{252}Cf , two different particles are taken as middle fragments with two complementary fragments in the collinear configuration. As the initial step, light-charged particles are considered, such as ^1H , ^2H , ^3H , ^4He , ^6Li , ^8Be . To understand the behavior of quaternary fission, the fragmentation potential (sum of binding energy, Coulomb potential, and proximity potential given in eq. 2.38) is studied. When A_3 is set as ^1H , ^2H , ^3H , ^4He , all feasible choices for A_4 are considered, including ^1H , ^2H , ^3H , ^4He , ^6Li , and ^8Be . The quaternary fission fragmentation potential is shown in Fig. 5.13 for spherical choice of nuclei. It shows that different middle fragments significantly affect the structure and magnitude of the fragmentation potential. A thorough examination of Fig. 5.13 shows that nearly symmetric fragments are prominent in the fission region. The lower magnitude corresponds to a more stable fragment combination. Therefore, the fragment combinations that correspond to lower potential energy are more likely to occur during the decay process. The minimized

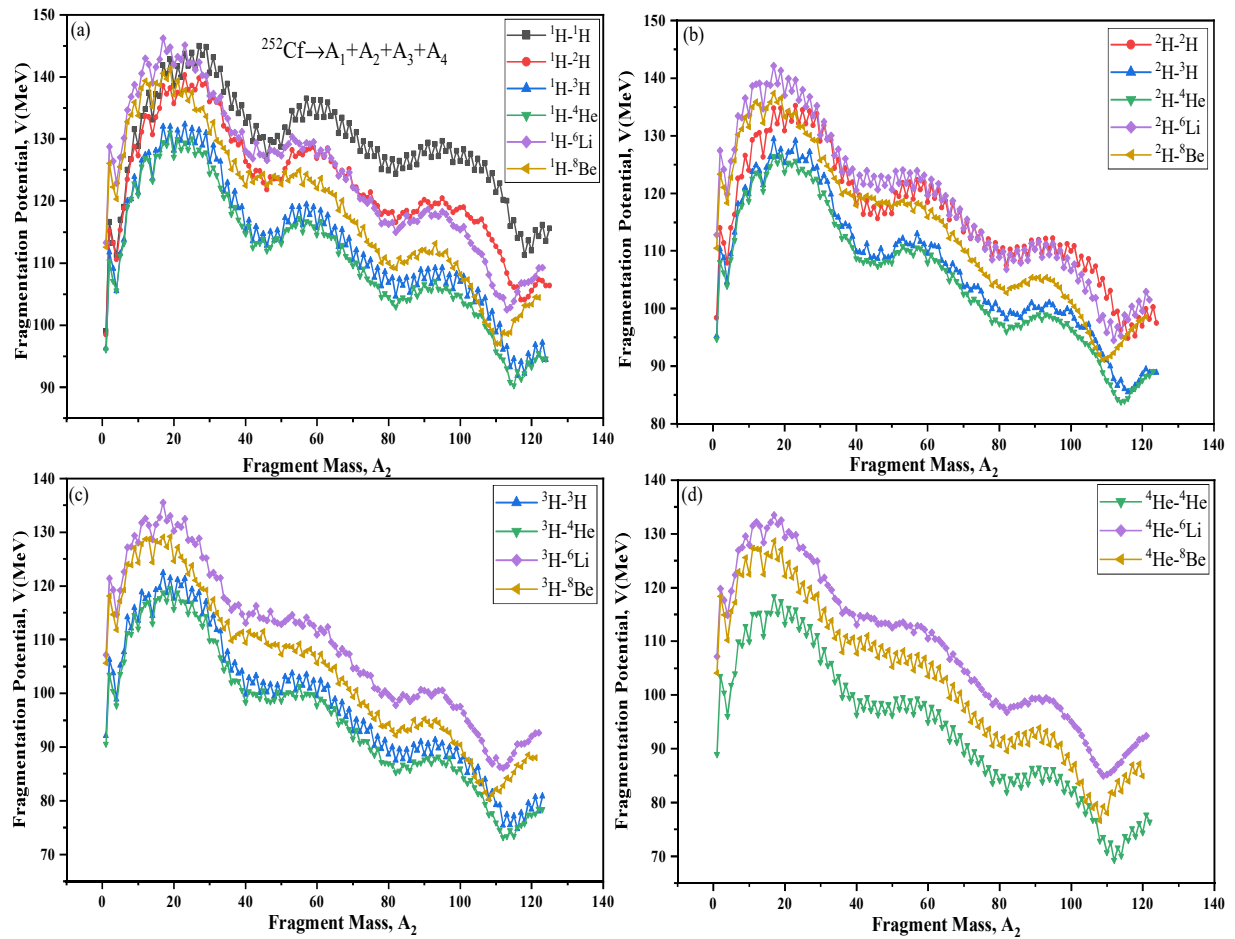


Figure 5.13: Quaternary fragmentation potential V (MeV) of ^{252}Cf nucleus with respect to the fragment mass A_2 .

combinations with their complementary fragments are listed in Table 5.2.

The observation could be attributed to the presence of shell closure, as one of the identified fission fragments exhibits either proton or neutron magicity. The neutron and proton magic numbers of complementary fragments are marked with bold letters in column 4 of Table 5.2. Column 5 of Table 5.2 represents the corresponding magnitude of the fragmentation potential. Among the various possible quaternary fission fragments, the fragments consisting of $^{132}\text{Sn} + ^4\text{He} + ^4\text{He} + ^{112}\text{Ru}$ yield the lowest magnitude of the fragmentation potential. This minimum suggests a higher likelihood for the system to undergo fission through this channel, rendering it the most probable quaternary breakup mode under the given theoretical framework. The enhanced stability of ^{132}Sn , being a doubly magic nucleus, and the presence of two α -particles likely contribute to the

Table 5.2: Fragment combinations for quaternary fission of ^{252}Cf nucleus at $s=0.0$ fm.

Cases	Light particles A_3 and A_4	Complementary Fragments $(A_1 + A_2)$	$(Z_1, N_1) + (Z_4, N_4)$	Fragmentation Potential $V(\text{MeV})$ of most probable fragment in fission valley
QF1	$^1\text{H} + ^1\text{H}$	$^{132}\text{Sn} + ^{118}\text{Pd}$	(50,82 46,72)	111.3
QF2	$^1\text{H} + ^3\text{H}$	$^{132}\text{Sn} + ^{116}\text{Pd}$	(50,82 46,70)	91.8
QF3	$^1\text{H} + ^4\text{He}$	$^{132}\text{Sn} + ^{115}\text{Rh}$	(50,82 45,70)	90.2
QF4	$^2\text{H} + ^3\text{H}$	$^{131}\text{Sn} + ^{116}\text{Pd}$	(50,81 46,70)	85.5
QF5	$^2\text{H} + ^4\text{He}$	$^{132}\text{Sn} + ^{114}\text{Rh}$	(50,82 45,69)	83.7
QF6	$^3\text{H} + ^3\text{H}$	$^{130}\text{Sn} + ^{116}\text{Pd}$	(50,80 46,70)	74.8
QF7	$^3\text{H} + ^4\text{He}$	$^{133}\text{Sb} + ^{112}\text{Ru}$	(51, 82 44,68)	73.1
QF8	$^4\text{He} + ^4\text{He}$	$^{132}\text{Sn} + ^{112}\text{Ru}$	(50,82 44,68)	69.2

Table 5.3: Fragment combinations for quaternary fission of ^{252}Cf nucleus for $s=0.0$ fm.

Cases	Light particles A_3 and A_4	Complementary Fragments $(A_1 + A_2)$	$(Z_1, N_1) + (Z_4, N_4)$	Fragmentation Potential $V(\text{MeV})$ of most probable Fragment in fission valley
QF1	$^{10}\text{Be} + ^1\text{H}$	$^{133}\text{Sb} + ^{108}\text{Mo}$	(51, 82 42,66)	89.40
QF2	$^{10}\text{Be} + ^2\text{H}$	$^{133}\text{Sb} + ^{107}\text{Mo}$	(51,82 42,65)	84.36
QF3	$^{10}\text{Be} + ^3\text{H}$	$^{133}\text{Sb} + ^{106}\text{Mo}$	(51,83 40,70)	74.17
QF4	$^{10}\text{Be} + ^4\text{He}$	$^{132}\text{Sn} + ^{106}\text{Mo}$	(50,81 40,62)	70.47
QF5	$^{10}\text{Be} + ^{10}\text{Be}$	$^{132}\text{Sn} + ^{100}\text{Zr}$	(50,82 40,60)	71.96

energetic emergence of this partition. The quaternary combination with higher magnitude of fragmentation potential have lower probability of occurrence. The complementary fragments are shown in Table 5.2. It is evident that ^{132}Sn emerges as the most favorable fragment in the majority of cases, compared to the neighboring isotopes such as ^{130}Sn and ^{133}Sb . This pronounced preference can be attributed to the doubly magic nature of ^{132}Sn , which possesses both proton and neutron shell closures at $Z = 50$ and $N = 82$, respectively. Theoretical investigations conducted by Poenaru *et al.* [?] highlight the prominent role of shell effects, particularly emphasizing the enhanced stability associated with the doubly magic nucleus ^{132}Sn in the context of quaternary fission of ^{252}Cf . Their analysis underscores the energetic favorability of fragment combinations that incorporate closed-shell configurations, which substantially lower the potential energy of the system and thus enhance the probability of such decay channels. The present study further corroborates this theoretical framework by confirming the influential role of the doubly magic nucleus in fragment formation during the quaternary fission process.

From an experimental [? ? ? ? ? ?] standpoint, there exists considerable evidence

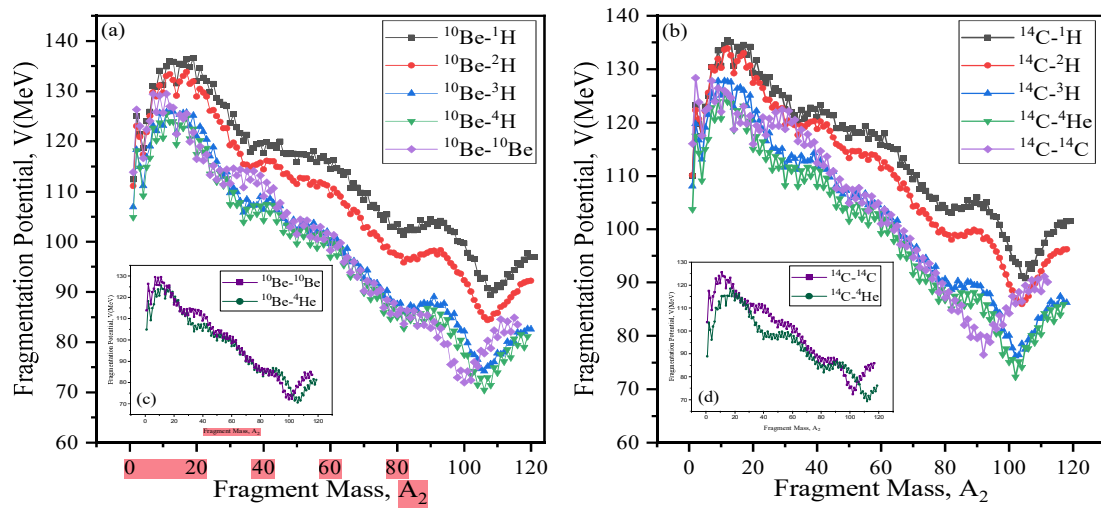


Figure 5.14: Quaternary fragmentation potential $V(\text{MeV})$ plotted for different combinations of middle fragments with respect to fragment mass A_2 .

Table 5.4: Fragment combinations for quaternary fission of ^{252}Cf nucleus for $s=0.0\text{fm}$.

Cases	Light particles A_3 and A_4	Complementary Fragments $(A_1 + A_2)$	$(Z_1, N_1) + (Z_2, N_2)$	Fragmentation Potential $V(\text{MeV})$ of most probable fragment in fission valley
QF1	$^{14}\text{C} + ^1\text{H}$	$^{132}\text{Sn} + ^{105}\text{Nb}$	(50,82 41,64)	90.7
QF2	$^{14}\text{C} + ^2\text{H}$	$^{132}\text{Sn} + ^{104}\text{Nb}$	(50,82 41,63)	85.9
QF3	$^{14}\text{C} + ^3\text{H}$	$^{133}\text{Sb} + ^{102}\text{Zr}$	(51,83 40,70)	76.2
QF4	$^{14}\text{C} + ^4\text{He}$	$^{132}\text{Sn} + ^{102}\text{Zr}$	(50,81 40,62)	72.3
QF5	$^{14}\text{C} + ^{14}\text{C}$	$^{132}\text{Sn} + ^{92}\text{Kr}$	(50,82 36,56)	76.4

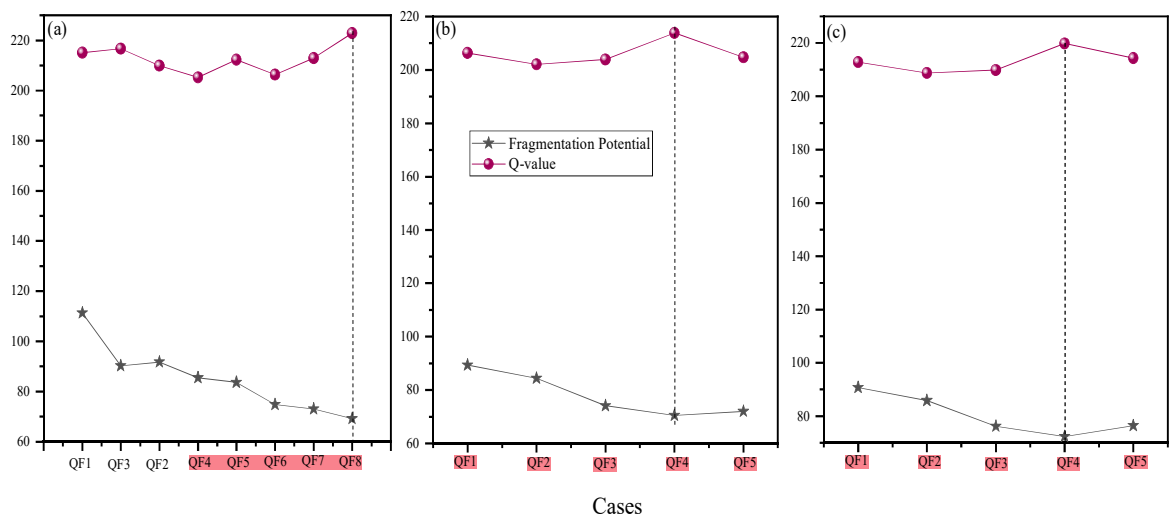


Figure 5.15: Fragmentation potential $V(\text{MeV})$ and Q -value (MeV) plotted with respect to the considered cases as described in (a) Table 5.2, (b) Table 5.3 and (c) Table 5.4.

supporting the emission of light-charged particles such as (α, α) , (α, t) , (p, p) , and (t, t) in multicluster fission events. Results (see Table 5.2) are in agreement with above analysis and help to explore the relevance of shell effects and fragment stability considerations in the decay dynamics.

In addition to the analysis of light charged particle emissions, further insights into the dynamics of multicluster fission can be obtained by examining the behaviour of the middle fragments, particularly in scenarios where one of them is a comparatively heavier particle. Charged particles such as ^{10}Be and ^{14}C have been experimentally observed in the ternary fission of ^{252}Cf , the present study initiates an investigation into the possibility of quaternary fission modes involving these clusters. Specifically, an effort is made to systematically explore various fragment combinations by incorporating ^{10}Be and ^{14}C as intermediate fragments in the quaternary decay of ^{252}Cf . The fragmentation potential of fragment combinations with respect to fragment mass A_2 is shown in Fig. 5.14. Fig. 5.14(a) illustrates that in the case of quaternary fragmentation involving ^{10}Be , the combinations with ^4He and ^{10}Be begin to exhibit comparable magnitude of fragmentation potential of the most probable fragment in the fission valley. These competing configurations are distinctly highlighted in the inset of the figure for better visualization and comparative analysis. The minima in the fission region is detailed in the Table 5.3. Similarly, quaternary fragment combinations involving ^{14}C are analyzed and depicted in Fig. 5.14(b), allowing for a comparative evaluation of energetically favorable configurations involving heavier light-charged clusters.

Furthermore, an in-depth analysis of the most probable fragment combinations corresponding to different intermediate (middle) fragments has been carried out by evaluating both the fragmentation potential and the associated Q-values. The results of this analysis are presented in Fig. 5.15. It is evident from the figure that the most probable fragment with lowest value of fragmentation potential combinations correspond to those exhibiting the highest Q-values. Furthermore, an in-depth analysis of the most probable fragment combinations corresponding to different intermediate (middle) fragments has been carried out by evaluating the fragmentation potential and the corresponding Q-values. The results of this analysis are presented in Fig. 5.16, where the Q-value is plotted as a function of the

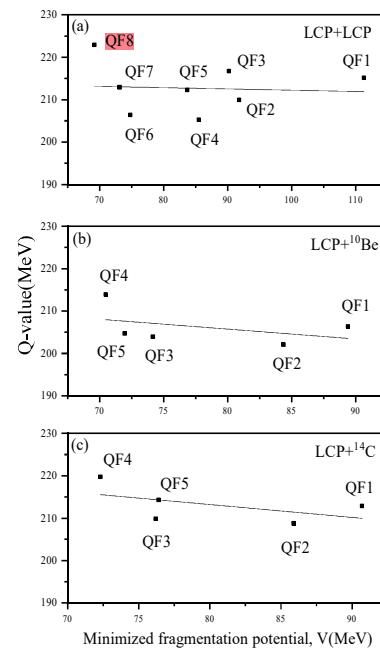


Figure 5.16: Fragmentation potential V (MeV) plotted with respect to Q -value (MeV) for different combinations of (a) Light charged particles (LCP) (b) LCP and ^{10}Be (c) LCP and ^{14}C .

the minimized fragmentation potential for different fragment combinations (cases) labelled as quaternary fragment (QF) corresponding to the Table 5.2, 5.3 and 5.4. A closer look at Fig. 5.16 reveals a general trend that Q -value decreases with a rise in the magnitude of the fragmentation potential. However, the relative contribution of two bigger fragments (A_1 and A_2) seem to influence this variation, and the magnitude of Q -value is relatively higher for the cases where A_1 and A_2 fragments have single/double magicity.

Ternary and quaternary fission

In addition to above analysis, ternary and quaternary fission with different configurations (equatorial and collinear) are explored. The ternary fragmentation potential of ^{252}Cf is calculated for different surface separation distances (s), specifically $s = -1.0, 0.0$, and 1.0 fm and is plotted with respect to fragment mass A_2 as shown in Fig. 5.17(a-c). The calculations are carried out to examine the impact of fragment spacing on the fragmentation potential. In this analysis, the third fragment is fixed as an α particle ($A_3 = {}^4\text{He}$). Furthermore, two geometric configurations are considered for the ternary breakup: the

Equatorial Cluster Tripartition (ECT) and the Collinear Cluster Tripartition (CCT). It may be noted that the deepest minima in the fragmentation potential correspond to the most probable fragment combination. Fig. 5.17(a-c) shows that the minima in the fission region corresponds to $^{132}\text{Sn}(Z=50, N=82) + ^4\text{He}(Z=2, N=2) + ^{116}\text{Pd}(Z=46, N=70)$ for different values of surface separation (s) and various configurations. This can be attributed to magic shell closure, as at least one of the fragments possesses closed proton and/or neutron shells, thereby lowering the potential energy. This observation is consistent with [?].

Therefore, one can conclude that the most probable fragment combination is independent of the surface separation distance (s) or the configuration considered. However, it should be noted that the magnitude of the fragmentation potential depends on the choice of configuration and the surface separation. A closer examination of Fig. 5.17 reveals that at the $s = -1.0$ and 0.0 fm, both the equatorial and collinear configurations exhibit comparable probabilities, indicating that either arrangement may be equally favored. However, as the surface separation between the fragments increases to $s = 1.0$ fm, a clear trend emerges wherein the collinear configuration becomes increasingly dominant. This suggests that at larger fragment separations, the linear alignment of fragments in the collinear geometry is energetically more favorable, likely due to reduced Coulomb repulsion and optimized fragment spacing in the potential landscape.

To further investigate the effect of surface separation on the ternary fission of the ^{252}Cf nucleus, the scattering potential ($V = V_{cij} + V_{Pij}$) has been evaluated. Fig. 5.18 illustrates the variation of this scattering potential as a function of the separation distance (s) for both the equatorial (ECT) and collinear (CCT) configurations. The first turning point, s_1 , is considered for three cases: $s = 1.0$ fm, $s = 0.0$ fm, and $s = -1.0$ fm. From Fig. 5.18(a), it can be observed that for the ECT configuration, all three cases are feasible since $V(s_1) \geq Q$ -value. In contrast, for the CCT configuration, only the $s = -1.0$ fm case appears feasible, as here $V(s_1) \geq Q$ -value. For $s = 0.0$ fm and $s = 1.0$ fm, the CCT configuration becomes unphysical as the first turning point $V(s_1)$ appears on the right side of V_B (barrier height). Whereas, for $s = -1.0$ to -0.5 fm, the scattering plot appears

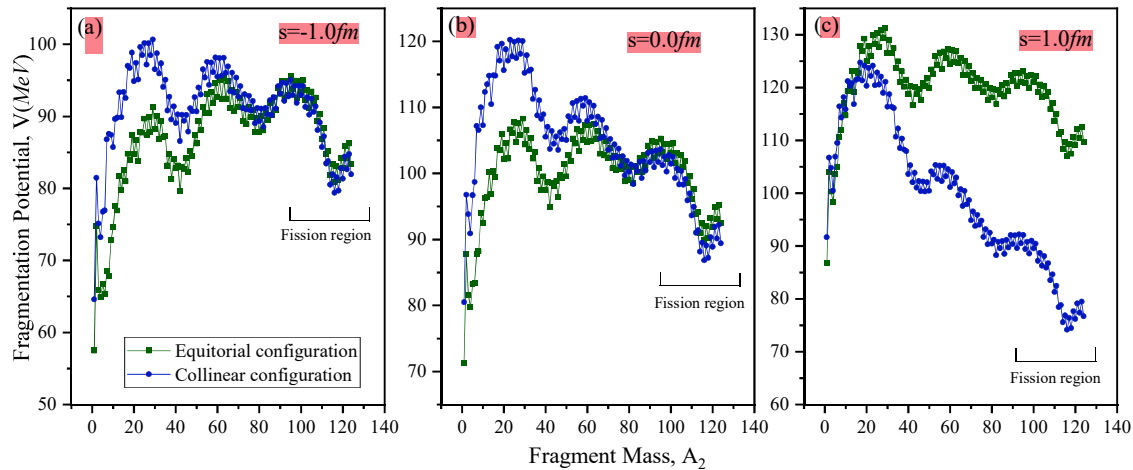


Figure 5.17: Fragmentation potential of ^{252}Cf plotted with respect to fragment mass A_2 considering equatorial and collinear configuration for (a) $s=-1.0\text{fm}$, (b) $s=0.0\text{fm}$ and (c) $s=1.0\text{fm}$.

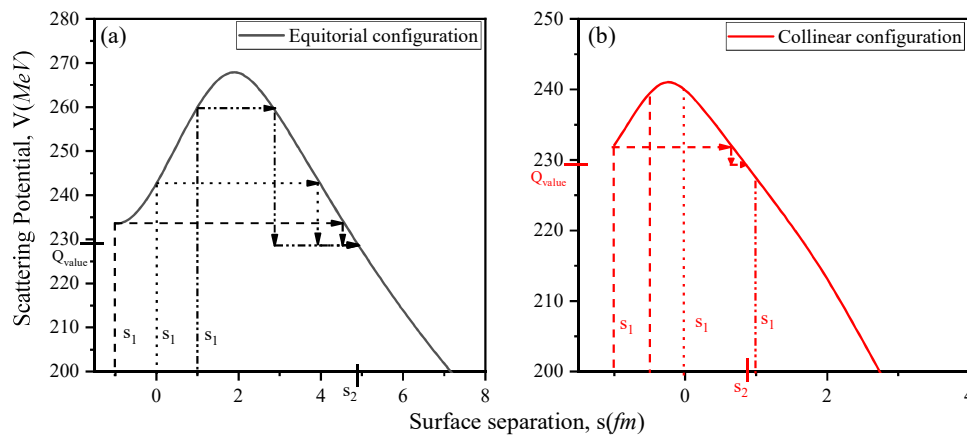


Figure 5.18: Scattering potential $V(\text{MeV})$ of ^{252}Cf nucleus plotted with respect to surface separation (s) by considering (a) equatorial and (b) collinear configuration.

feasible, as depicted in Fig. 5.18(b). In the present case, the surface separation distance has been varied uniformly for both the ECT and CCT configurations while keeping the radii of the corresponding fragments unchanged. The objective is to examine the effect of the surface separation on the barrier characteristics of the fragments emerging in these two configurations. It is observed that the barrier height is lower for the CCT configuration compared to the ECT case. These results are consistent with the findings reported in Ref. [?].

Following the ternary analysis, a corresponding investigation of the quaternary fission

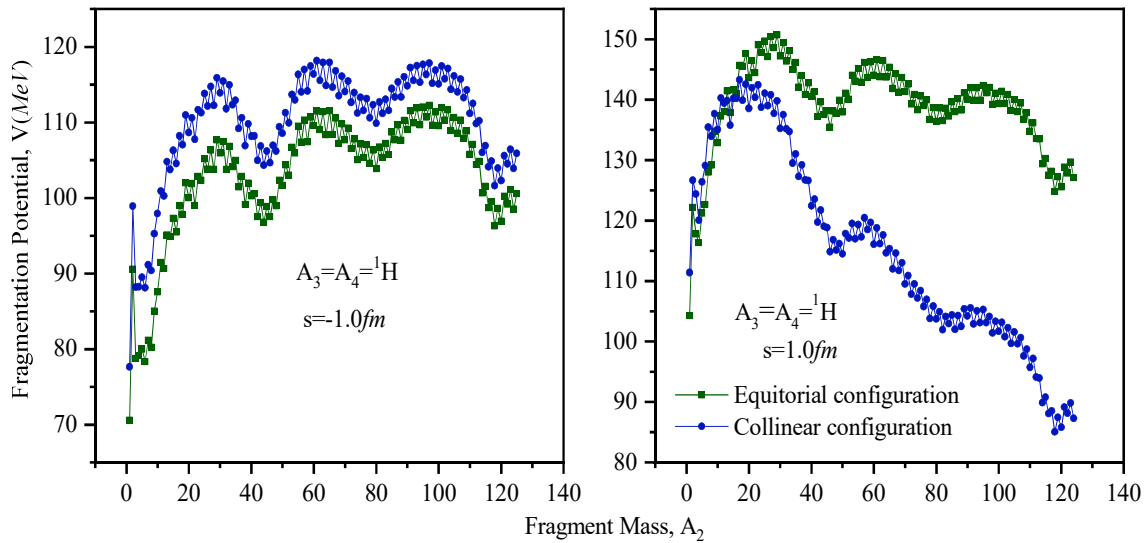


Figure 5.19: Fragmentation potential of ^{252}Cf plotted with respect to fragment mass A_2 considering Equatorial and collinear configuration for (a) $A_2=A_3=^1\text{H}$ (b) $A_3=^1\text{He}$, $A_4=^4\text{He}$ for $s=-1.0\text{fm}$ and $s=1\text{fm}$.

of the ^{252}Cf nucleus is undertaken. In this context, two light charged particles are considered as the middle fragments, accompanied by two complementary heavier fragments. The third and fourth fragments—designated as the middle fragments—are assumed to be fixed in each case, while mass asymmetry is introduced between the two complementary fragments. As an initial step, light charged particles such as ^1H , ^2H , ^3H , and ^4He are selected as candidates for the third fragment (A_3). For each choice of A_3 , all feasible cases for the fourth fragment (A_4) are systematically explored. Subsequently, the quaternary fragmentation potential of ^{252}Cf is computed by considering various combinations of the light middle fragments within the equatorial and collinear configuration (as shown in Fig. 2.4), at a surface separation distance of $s = -1.0\text{ fm}$. These calculations are performed under the assumption of spherical shape of the fragments. The most favorable fragmentation combinations ($A_1 + A_2 + A_3 + A_4$) are observed as $^{132}\text{Sn} + ^{118}\text{Pd} + ^1\text{H} + ^1\text{H}$, $^{131}\text{Sn} + ^{118}\text{Pd} + ^1\text{H} + ^2\text{H}$, $^{132}\text{Sn} + ^{116}\text{Pd} + ^1\text{H} + ^3\text{H}$, $^{132}\text{Sn} + ^{115}\text{Rh} + ^1\text{H} + ^4\text{He}$, $^{132}\text{Sn} + ^{116}\text{Pd} + ^2\text{H} + ^2\text{H}$, $^{131}\text{Sn} + ^{116}\text{Pd} + ^2\text{H} + ^3\text{H}$, $^{132}\text{Sn} + ^{114}\text{Rh} + ^2\text{H} + ^4\text{He}$, $^{130}\text{Sn} + ^{116}\text{Pd} + ^3\text{H} + ^3\text{H}$, $^{133}\text{Sb} + ^{112}\text{Ru} + ^3\text{H} + ^4\text{He}$, $^{132}\text{Sn} + ^{112}\text{Ru} + ^4\text{He} + ^4\text{He}$. One of the consistent findings of the present analysis is that the most probable fragment, corresponding to the minimum in the fragmentation potential, remain independent of

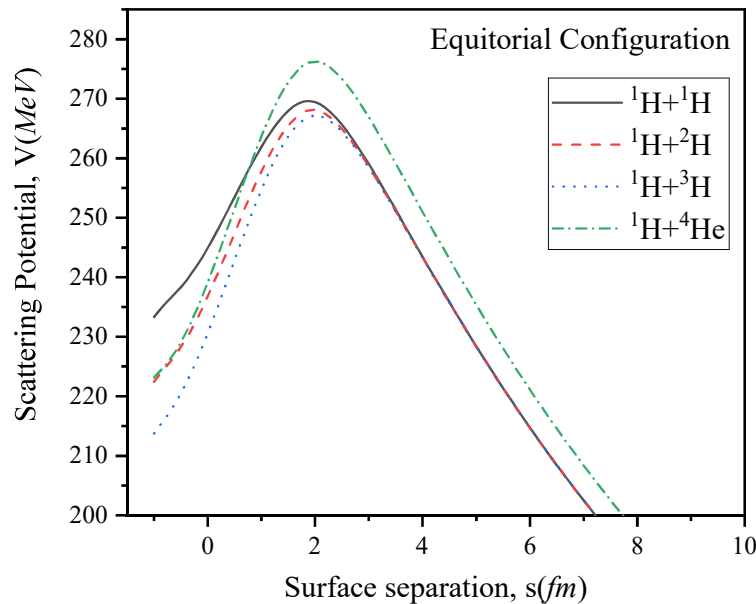


Figure 5.20: Scattering potential $V(\text{MeV})$ of ^{252}Cf nucleus plotted with respect to surface separation (s) by considering equatorial configuration.

the geometrical configuration (equatorial or collinear). To illustrate the effect of varying s , the fragmentation potential for one representative case has also been calculated at $s = -1.0$ and 1.0fm and is shown in Fig. 5.19(a-b). Fig. 5.19 demonstrates that at $s = -1.0\text{ fm}$, both the equatorial and collinear configurations exhibit competitive behavior, whereas at $s = 1.0\text{ fm}$, the collinear configuration appears more probable due to the lower magnitude of the fragmentation potential. However, as discussed earlier, $s = -1.0\text{ fm}$ represents the more realistic case and is therefore adopted for the calculations.

Further, the scattering potential for the quaternary fission has been calculated for the equatorial configuration, considering the middle fragment combinations $^1\text{H} + ^1\text{H}$, $^1\text{H} + ^2\text{H}$, $^1\text{H} + ^3\text{H}$, and $^1\text{H} + ^4\text{He}$. The results are plotted as a function of surface separation (s) and are presented in Fig. 5.20. A closer examination of the figure reveals that the magnitude of the scattering potential varies significantly with the choice of middle fragments ($^1\text{H} + ^1\text{H}$, $^1\text{H} + ^2\text{H}$, $^1\text{H} + ^3\text{H}$), exhibiting lower potential barriers, thereby indicating a higher likelihood of occurrence. In contrast, heavier combination like $^1\text{H} + ^4\text{He}$ show relatively higher potential barriers, suggesting a reduced probability of emission. This behavior can

be attributed to the interplay of Coulomb repulsion and nuclear proximity effects, which strongly influence the energetics of the quaternary fission.

5.3 Summary

Initially, the binary fragmentation potential is employed and ^4He , ^{46}Ar , ^{82}Ge and ^{116}Pd are identified as most probable fragments along with their complementary fragments. After the fragmentation analysis, the barrier characteristics of these probable channels are compared and alpha decay is found as the most probable decay mode. In the next step, the ternary fission analysis of ^{252}Cf nucleus is made by keeping ^4He , ^{46}Ar and ^{82}Ge as fixed third fragments. It is observed that the magnitude and structure changes significantly as one moves from a lighter to a heavier third fragment. The identified minima in the fragmentation potential are attributed to the presence of shell closure. After the identification of the most probable two and three-fragment combinations, the quaternary fission analysis has been made. A comparison of all probable arrangements for collinear configuration in quaternary fission is worked out, and the one arrangement with elongated neck between two heavy fragments is found as most probable. In the light fragment-accompanied quaternary fission modes, $(A_1, \alpha, \alpha, A_2)$ and (A_1, α, t, A_2) are found as most probable cases.

After studying light fragment emission, an attempt is made to explore the heavy fragment emission mechanism. It is observed that the fragmentation structure varies significantly with an increase in the mass of the third and fourth fragments. A secondary dip is observed when the mass of the third fragment becomes 25% and 13% of the parent for ternary and quaternary fission, respectively. The fragment combinations of ternary and quaternary fission along the fission axis are identified. The suggested combinations in reference to ternary decay include $^{48-52}\text{Ca}$ nuclei along with $^{68-74}\text{Ni}$ and $^{129-133}\text{Sn}$ isotopes. Which is in alignment with the available experimental data. Similarly, ^{34}Si , ^{46}Ar , and $^{48-52}\text{Ca}$ have been identified as third and fourth ($A_3'' = A_4''$) fragments in the quaternary fission. The experimental verification of these will be of future interest. Further, the relative yield and fragmentation potential are analysed as a function of fragment mass for two distinct choices of surface separation ($s=0$ fm and $s=1$ fm). The results indicate that the overall

behaviour of yield is in consistent with the fragmentation structure.

In order to understand the influence of the different combinations of the middle fragments on the fragmentation potential, the combinations of light fragments such as ^1H , ^2H , ^3H , ^4He , ^6Li , and ^8Be are considered. The study further explores heavier clusters such as ^{10}Be and ^{14}C , reinforcing the significance of shell effects and energy minimization in the dynamics of multicluster emissions. Finally, the analysis of ternary and quaternary fission are performed with particular emphasis on surface separation effect by adopting two geometrical configurations (collinear and equatorial). For ternary fission, calculations show that the most probable fragment combinations ^{132}Sn ($Z = 50, N = 82$) + ^4He ($Z = 2, N = 2$) + ^{116}Pd ($Z = 46, N = 70$) are independent of surface separation, although there is significant difference in the magnitude of fragmentation potential, particularly at higher separation distance. In addition, the quaternary fission analysis is performed for both equatorial and collinear configurations, considering various light charged particles as middle fragments.

After a comprehensive exploration of binary, ternary and quaternary fission processes, attention is now focused on the Skyrme based nuclear interaction potential. In the first stage, ground-state decay modes, encompassing both binary and ternary fission channels, are systematically investigated using the proximity potential and Skyrme energy density formulism SEDF based approach. Subsequently, the SEDF-based formalism is extended to the study the excited state decay process. These results are reported in the next chapter

CHAPTER 6

Decay dynamics using Skyrme based nuclear potential

6.1 Introduction

To fully understand the dynamics of nuclear interactions, selecting an appropriate nuclear interaction potential is crucial. Theoretical models play a highly constructive role in describing nuclear interactions at both macroscopic and microscopic levels. In recent years, various theoretical models have been developed to explain different aspects related to formation and decay dynamics of the nuclear systems. The two commonly used approaches for calculating nucleus-nucleus potentials are the phenomenological and microscopic methods [1–4]. Phenomenological potentials, such as those derived by Blocki *et al.* [5–8], are based on empirical models, while microscopic potentials may be obtained using the well-known Skyrme energy density formalism (SEDF) [9–11]. Such potentials provide a framework for understanding the nuclear forces governed during the complex interactions such as nuclear fusion, fission, and radioactive decay processes etc [12–15].

This study concentrates on exploring the nuclear interaction potentials specifically, proximity and SEDF based potentials in reference to the decay mechanism, with a particular focus on binary and ternary decay modes. There is substantial support from experimental [16–19] and theoretical [20–23] studies for the existence of binary and ternary decay pathways in ^{252}Cf . In addition to the ground-state decay process, it is important to consider scenarios in which the decaying system is formed in an excited state. When a projectile collides with a target at varying beam energies, a compound nucleus (CN) can be formed in an excited state. This excited CN is in an unstable state and

subsequently de-excites to the lower/ground state by breaking up into binary fragments under various extremities, such as excitation energy (or temperature), angular momentum, nuclear deformations and relative orientations etc. Consequently, the relative dominance of probable decay mechanisms, viz., evaporation residues (ER) or equivalently light-charged particles, intermediate mass fragments (IMF), heavy-mass fragments (HMF) and fission, varies with respect to the excitation energy (E_{CN}^*) and mass number of CN. As a consequence, the emission of fragments act as a source of producing new elements/isotopes, which would help in extending the nuclear Periodic Table.

In this context, the theoretical investigations developed on the basis of micro/macroscopic calculations help to recognize the fission fragments [? ? ? ? ? ? ? ? ? ? ? ? ? ?]. In the present work, the collective clusterization approach is opted which is used within DCM [? ?]. The efforts were made to identify the most favorable fission fragments obtained through the mass and charge dispersion analysis.

Hence, to understand the reaction dynamics involving a radioactive beam, i.e. Aluminium-31 (^{31}Al), hitting on a stable target Gold-197 (^{197}Au) over a wide range of beam (or center of mass) energies $E_{\text{c.m.}}$ is studied. Experimentally [?], the σ_{fis} have also been obtained for $^{31}\text{Al} + ^{197}\text{Au} \rightarrow ^{228}\text{U}^*$ reaction, at $E_{\text{c.m.}}$ lying near, above and far away from the Coulomb barrier. Note that, for the above said reaction, $Z_1 Z_2 = 1027$, where the quasi fission (QF) compared may also creep in. To examine the amount of σ_{QF} in reference to the fission cross-sections for $E_{\text{c.m.}} = 106.2 - 163.2$ MeV (or $E_{\text{CN}}^* = 30.8 - 87.8$ MeV), initially, obtained $\sigma_{\text{fis}}^{\text{Theo}}$ using DCM and compared the results with $\sigma_{\text{fis}}^{\text{Expt}}$. The difference observed between $\sigma_{\text{fis}}^{\text{Theo}}$ and $\sigma_{\text{fis}}^{\text{Expt}}$ has been addressed as the content of QF event. The above analysis would be tested for energies which are lying near, above and far away from the Coulomb barrier. In addition to this, we have also done the fission and quasi-fission analysis for $^{19}\text{F} + ^{209}\text{Bi} \rightarrow ^{228}\text{U}^*$ reaction, and compared the obtained results with the available data [?] for $E_{\text{CN}}^* = 31.5 - 66.0$ MeV.

It is relevant to note that for ground state analysis, Preformed cluster model (PCM) is used where for the decay of CN formed in ^{19}F induced reaction dynamical cluster decay model (DCM) is adopted. Based on the preceding discussion, the primary objective of this chapter are outlined as follows:

1. Ground-State Decay of ^{252}Cf

- (i) to analyze the binary decay with proximity potential and potential based on SEDF;
- (ii) to examine the role of deformations and orientations of the decay fragments in the fragmentation structure and preformation probability; and (iii) an analysis of particle-accompanied ternary fission of the ^{252}Cf is done by considering the third fragment as ^4He .

2. Excited-State Decay of $^{228}\text{U}^*$

- (i) the product of charge numbers of considered P-T combination, (ii) the range of E_{CN}^* , (iii) the choice of incident beam, and (iv) the Businaro-Gallone mass asymmetry (α_{BG}) parameter. The above analysis is tested using SIII and SSk Skyrme forces.

The organization of this chapter is as follows: Section 6.2 presents the theoretical calculations and the corresponding results related to the present study. Section 6.3 provides a concise conclusion based on the major findings of this work. The part of this chapter has been published in ref. [?].

6.2 Discussion

The Section 6.2.1, focuses on the binary and ternary decay processes of the ^{252}Cf nucleus. The corresponding calculations and results for both decay modes are thoroughly examined. Whereas, in Section 6.2.2 the results pertaining to the fission behaviour of the $^{228}\text{U}^*$ CN, formed in the $^{31}\text{Al} + ^{197}\text{Au}$ and $^{19}\text{F} + ^{209}\text{Bi}$ reactions, are discussed.

6.2.1 Ground-State Decay of ^{252}Cf

Binary decay of ^{252}Cf

In order to comprehend the nuclear dynamics of a radioactive nucleus, an effort is made to understand the binary decay of ^{252}Cf . Previous investigations have examined the disintegration of actinides into two fragments, giving rise to different exit channels such as i.e. α decay, CR, HPR, and SF using the Prox 77 potential [? ?]. These studies demonstrated that the half-lives of various decay modes can be evaluated under both

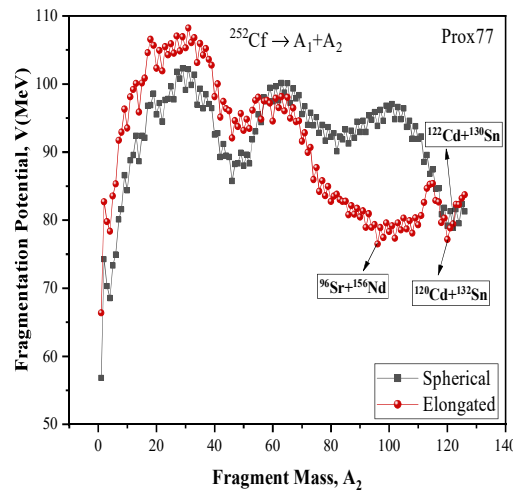


Figure 6.1: Fragmentation potential of ^{252}Cf nucleus plotted with respect to the fragment mass A_2 .

spherical and hot-compact configurations. Whereas, in the present work, attention is directed toward the decay of ^{252}Cf nucleus, incorporating the cold-elongated configurations. Therefore, the fragmentation potential for ^{252}Cf is calculated by employing proximity (prox 77 [?]) potential, as shown in Fig. 6.1 .

Table 6.1: The PCM-calculated half-life for spontaneous fission along with the fitted neck-length parameter ΔR are presented. The choice of the outgoing fragment is based on the most probable fragment having the highest preformation probability. Note that in each case, spherical as well as β_2 -deformations are taken into consideration. The calculated half-lives are also compared with experimental data [?].

Parent nucleus	Decay channel	ΔR (fm)	$\log_{10} T_{1/2}^{Exp.}$ (sec)	$\log_{10} T_{1/2}^{PCM}$ (sec)
^{252}Cf	$^{122}\text{Cd}+^{130}\text{Sn}$	Spherical		
		0.125	9.43	9.04
^{252}Cf	$^{120}\text{Cd}+^{132}\text{Sn}$	Deformed		
		-0.522	9.43	9.40

The results indicate that symmetric fragments are favored at spherical magic shell closure ($Z = 50$, $N = 82$) and asymmetric fragments near deformed magic shell ($Z = 38$, $N = 60$), emphasizing the role of nuclear shell effects in determining the fragment mass distributions. It may be noted here that this study incorporates deformation effects up to quadrupole (β_2) with cold-elongated orientations. Further, the half-lives are calculated for the elongated configuration. The calculated half-lives are found to underestimate the experimental SF data. It should be noted that the half-life increases with decrease in ΔR

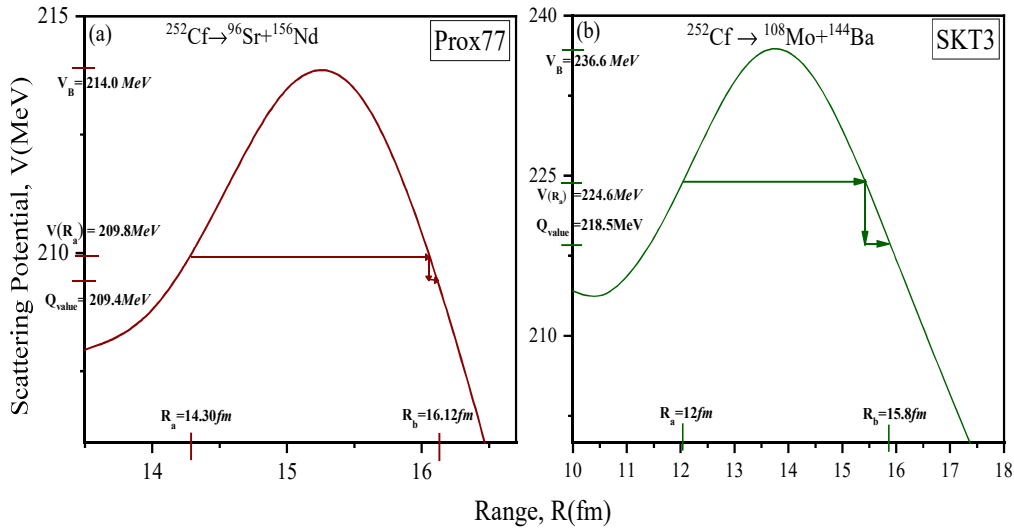


Figure 6.2: PCM calculated scattering potential for (a) Prox 77 and (b) skyrme force with elongated configuration for asymmetric fission of the ^{252}Cf nucleus.

(neck-length parameter). However, in this case, ΔR cannot be reduced further as $V(R_a)$ (see fig 6.2) becomes less than the Q -value of the decaying fragments. Consequently, the fragments would be unable to penetrate the barrier, preventing the decay process from occurring.

Theoretical investigations indicate that by modifying the characteristics of the potential barrier, it is possible to achieve the half-lives. Therefore, an attempt is made to address this by incorporating nuclear potential based on SEDF [?]. It is observed that there is still a lowering in the barrier characteristics for skyrme forces such as SIII, GSKI and SKT2 [?]. Therefore, further analysis was conducted by exploring skyrme forces imparting a higher barrier potential, such as SKT3 [?] parameter sets. Eventually, SKT3 force was employed to get the optimum barrier characteristics as shown in Fig. 6.2. This choice of decaying fragments was substantiated by selecting the decaying fragments from the minima of the fragmentation potential, a process detailed later in Fig. 6.3. It is evident from Fig. 6.2 that the potential barrier is significantly modified depending on the nuclear potential employed.

Hence, by considering the Skyrme SKT3 force [?], a more in-depth analysis of the decay dynamics is conducted. The collective fragmentation potential $V_R(\eta)$ of ^{252}Cf is plotted in

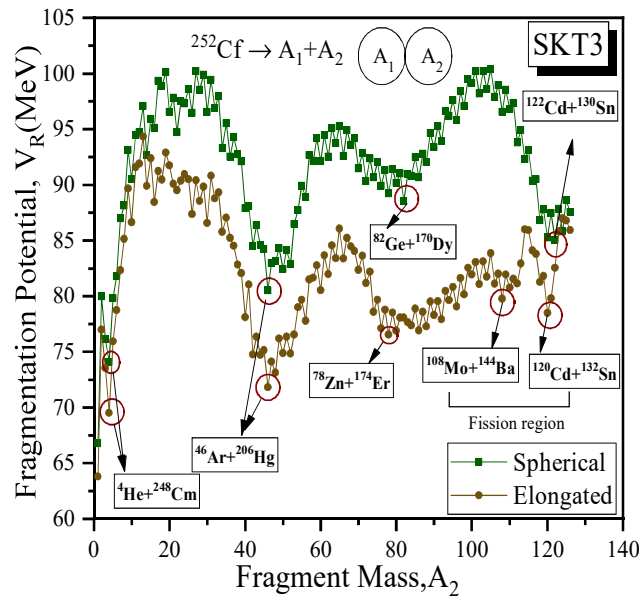


Figure 6.3: Fragmentation potential of ^{252}Cf with respect to fragment mass A_2 .

Fig. 6.3 as a function of the fragment mass A_2 for the choice of spherical and cold-elongated configurations. The structure of the fission valley undergoes substantial modification upon the inclusion of deformation and orientation effects. For the spherical approach, the dips in the fragmentation potential indicate α decay ($^4\text{He}(Z=2, N=2) + ^{248}\text{Cm}(Z=96, N=152)$), CR ($^{46}\text{Ar}(Z=18, N=28) + ^{206}\text{Hg}(Z=80, N=126)$), HPR ($^{82}\text{Ge}(Z=32, N=50) + ^{170}\text{Dy}(Z=66, N=104)$) and SF ($^{122}\text{Cd}(Z=48, N=74) + ^{130}\text{Sn}(Z=50, N=80)$) are the main contributors. However, in the cold-elongated configuration, the dips of α -decay and CR remain the same. Whereas the dip at $^{78}\text{Zn}(Z=30, N=48) + ^{174}\text{Er}(Z=68, N=88)$ corresponds to HPR. In fission region, asymmetric fission fragments ($^{108}\text{Mo}(Z=42, N=86) + ^{144}\text{Ba}(Z=56, N=88)$) also contribute to SF alongside the fragment pair $^{120}\text{Cd}(Z=48, N=72) + ^{132}\text{Sn}(Z=50, N=82)$. The fission region is highlighted in Fig. 6.3, indicating that nearly symmetric fragments constitute the primary contributors to the SF of ^{252}Cf parent nucleus for the spherical case. However, in the cold-elongated configuration, asymmetric fission fragments also start their contribution towards the spontaneous fission. The half-lives of identified fragments are calculated by using the only parameter of the model, i.e., the “neck-length” parameter (ΔR). Table 6.1 represents that the PCM calculated half-lives exhibit reasonable agreement with the experimental data [?]. The corresponding

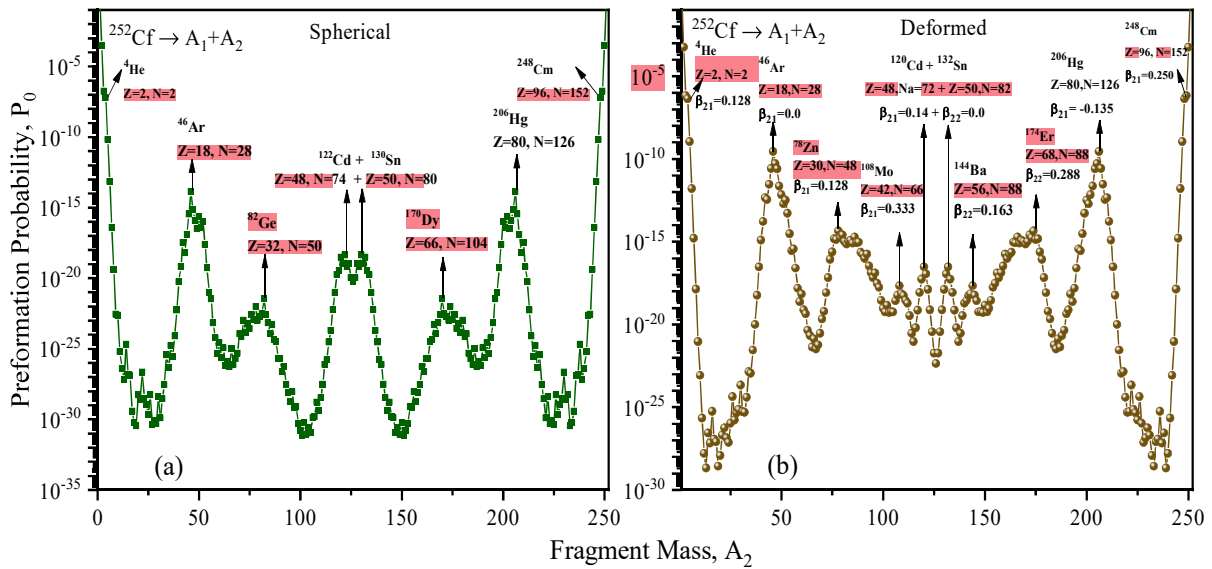


Figure 6.4: The preformation probability is plotted with respect to fragment mass A_2 with SKT3 force.

half-lives, neck-length parameters, and the most probable fragments are summarized in Table 6.1.

Fig. 6.3 shows that a cold-elongated configuration gives a lower potential, whereas the potential is relatively high for a spherical configuration. This phenomenon is rooted in the diminishing influence of spherical shell effects with the incorporation of elongated orientations and the increasing influence of deformed shell closure. It signifies that the binary decay of ^{252}Cf is more probable via elongated configuration. Furthermore, it would be valuable to investigate the underlying causes and implications of the formation of symmetric and asymmetric fragments in the cold-elongated configuration.

For further analysis, the preformation probability of ^{252}Cf nucleus is calculated for spherical as well as for elongated configuration. The results of the preformation probability are shown in Fig. 6.4 with the one plotted for fragmentation potential in Fig. 6.3. The positions of nascent fragments in Z and N numbers and the most probable fragments are identified in reference to the peaks of the P_0 and shown in Fig. 6.4(a-b). The corresponding deformations of these fragments are also indicated. The symmetric peak is mainly governed by spherical shell closure of the proton number at $Z=50$ neutron shell closure of $N=82$. In contrast, the emergence of asymmetric fission fragments can be

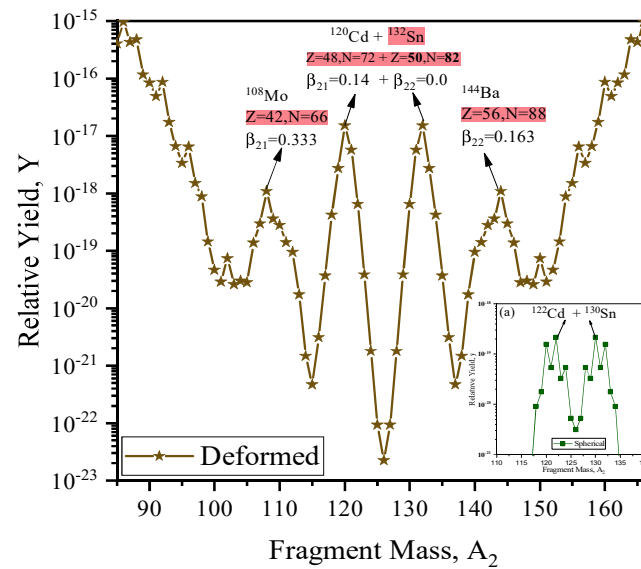


Figure 6.5: The preformation probability is plotted with respect to fragment mass A_2 with SKT3 force.

attributed to the presence of nuclear deformations. This indicates that deformations play a crucial role in identifying the decaying fragments. This comparative approach allows for a comprehensive understanding of how the shape of the nucleus influences the fragmentation potential and, consequently, the fission process.

In addition to this, the relative yield of the binary fission fragments is calculated using the relation $Y(A_2) = P_o(A_2) / \sum P_o(A_2)$ as a function of decaying fragment A_2 . The results are shown in Fig. 6.5. The subset (a) of Fig. 6.5 represents the yield with spherical choice. The results indicate that the structure of the spherical yield closely resembles the experimental fission yield [? ?] but the identified fragments, i.e., ^{122}Cd ($Z=48, N=74$) + ^{130}Sn ($Z=50, N=80$) are more symmetric. Where in the deformed case (Fig. 6.5) the contributing fragments are same, i.e., $(^{108}\text{Mo} (Z=42, N=86) + ^{144}\text{Ba} (Z=56, N=88))$ as experimental observation, but dominance of a peak near more symmetrical fragments, i.e., $^{120}\text{Cd} (Z=48, N=72) + ^{132}\text{Sn} (Z=50, N=82)$. Therefore, it can be concluded that the decay dynamics of ^{252}Cf suggests the possibility of asymmetric spontaneous fission. This indicates that the obtained results are in good agreement with the available experimental data. Further, the ternary fission of ^{252}Cf nucleus is explored in the next subsection.

Ternary fission of ^{252}Cf

Interestingly, there is the possibility of ternary fission from ^{252}Cf nucleus [? ? ? ?]. Therefore, the model introduced is extended for ternary fission, and SEDF-based potential is used to understand the ternary decay of ^{252}Cf nucleus. As a first step, the ternary fragmentation potential is calculated for ^{252}Cf nucleus by considering the equatorial configuration with a fixed spherical third fragment ($A_3 = {}^4\text{He}$) using eqn.2.28 and plotted as a function of mass number A_2 in Fig. 6.6. For this analysis, the surface separation (s) is fixed at $s = 1.0$ fm [?]. Notably, the calculations incorporate both spherical and deformed configurations of the decaying fragments, with the third fragment being spherical. For the deformed cases, the optimum orientations are selected based on a cold-elongated configuration, as previously described. Fig. 6.6 shows that the magnitude and the structure of fragmentation potential vary as one moves from spherical to cold-elongated configuration. The difference in magnitude arises from the inclusion of the deformation parameter. However, at points where the deformation contributions are negligible, the spherical and deformed potentials coincide, indicating that the potential values are identical. The overall structure of the fission valley gets modified with the inclusion of deformations. The fission region is marked in Fig 6.6, where the potential for the cold-elongated configuration is lower compared to the spherical configuration because the interaction radius is largest for the earlier case. This phenomenon arises from the diminishing influence of spherical shell effects with the incorporation of elongated orientations and the increasing influence of deformed shell closures. Notably, the nuclei in the fission region ($80 \leq A_2 \leq 110$) have high deformations ($\beta_2 \geq 0.3$) which potentially influence the structure of fragmentation potential.

Focusing on the spherical approach ($\beta_2 = 0$), the dip in the fission region suggests that nearly symmetric fragments ($^{116}\text{Pd}(Z=46, N=70) + ^{132}\text{Sn}(Z=50, N=82)$) contribute to the ternary fission of the ^{252}Cf nucleus. However, in the cold-elongated configuration, asymmetric fragments ($^{108}\text{Mo}(Z=42, N=66) + ^{140}\text{Xe}(Z=54, N=86)$) also begin to contribute alongside symmetric ($^{116}\text{Pd}(Z=46, N=70) + ^{132}\text{Sn}(Z=50, N=82)$) fragments. The results depict that the deepest minima in the fragmentation potential corresponds to the deformed fragments in the ternary decay of ^{252}Cf , which signifies that the deformed channel

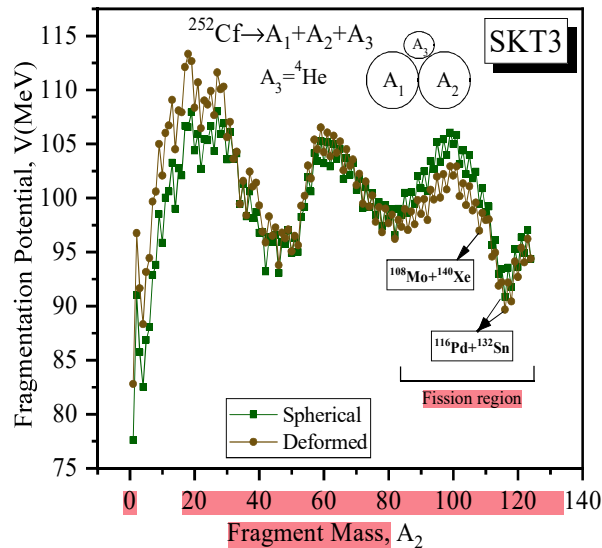


Figure 6.6: The fragmentation potential is plotted with respect to fragment mass A_2 .

is more probable. For the further analysis of the fission region, the barrier characteristics of the ternary decay of ^{252}Cf nucleus are analyzed by plotting the scattering potential in Fig. 6.7 with respect to surface separation (s). The barrier characteristics for the most probable fragments ($^{116}\text{Pd}(\beta_{21} = -0.250) + ^{132}\text{Sn}(\beta_{22} = 0.00)$) are analyzed in reference to spherical and cold-elongated cases as shown in Fig. 6.7(a) and Fig. 6.7(b), respectively. It may be noted that the calculations are performed at a surface separation $s = 1.0$ fm. For barrier penetration to occur, the scattering potential $V(s_1)$ at the first turning s_1 must exceed the Q value of the decay process (as discussed in Sec. IIIA). It is evident from Fig. 6.7 that the barrier characteristics are modified with the inclusion of deformation and orientation effects. Notably, the barrier height is lower for the deformed case (as shown in Fig. 6.7(b)), indicating that it is a more probable decay compared to the barrier with a higher barrier height. This underscores a greater likelihood of decay involving deformed fragments than spherical ones. The scattering potential results are in good agreement with those obtained from the fragmentation potential, thereby confirming that deformed configurations of the decaying nuclei are the more probable.

Additionally, the relative yield within the fission valley for the ternary fission of ^{252}Cf

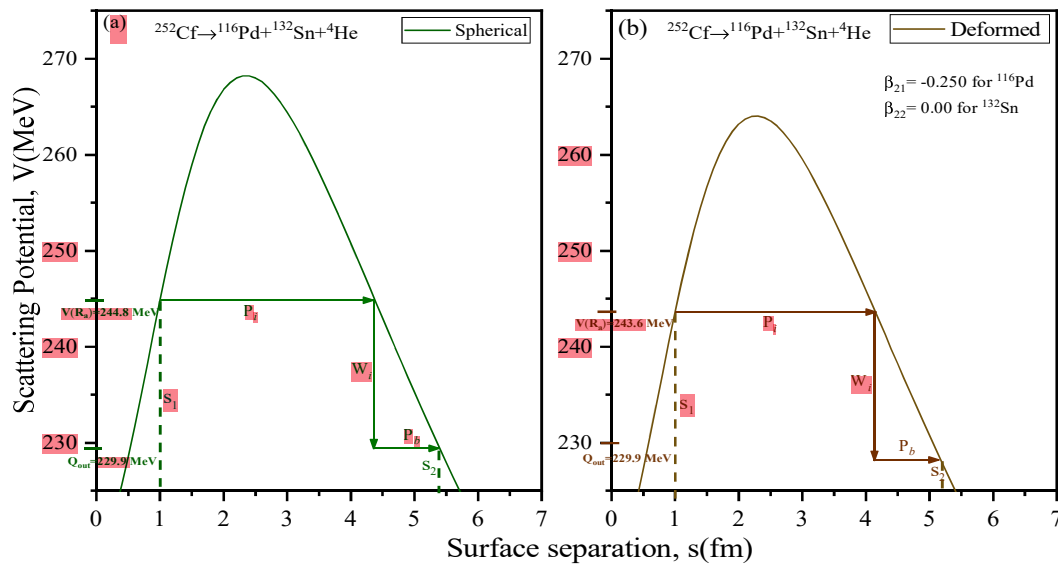


Figure 6.7: PCM calculated scattering potential for (a) proximity and (b) skyrme force with elongated configuration for asymmetric fission of the ^{252}Cf nucleus.

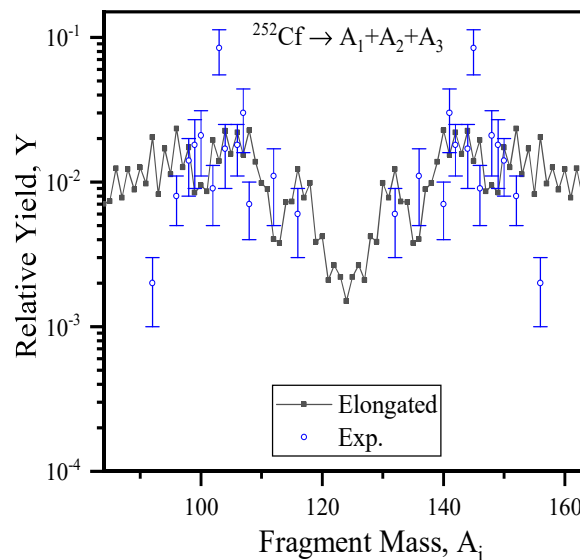


Figure 6.8: The relative yield is plotted with respect to fragment mass A_i .

is examined by adopting a deformed (cold-elongated) configuration for the decaying fragments. Given that deformed fragments are more likely to occur, the yield calculations focus specifically on the elongated case. The relative yield is determined as the ratio of the penetration probability of a specific fragment to the sum of the penetration probabilities for all possible fragmentation channels. In the present study, ECT configuration is employed by taking $A_3=^4\text{He}$ for the spontaneous ternary fission of ^{252}Cf , as illustrated in Fig. 6.8. Fig. 6.8 also presents the comparison of calculated ternary yield for the ^4He -accompanied spontaneous ternary fission of ^{252}Cf with available experimental data [?]. After the decay dynamics of radioactive nucleus ^{252}Cf . I have shown the results of the correspond nuclear dynamics in the next section.

6.2.2 Decay dynamics of $^{228}\text{U}^*$ compound nucleus

In the present work fission dynamics of excited CN system $^{228}\text{U}^*$, formed via $^{31}\text{Al}+^{197}\text{Au}$ reaction, for a range of $E_{\text{c.m.}}$ is studied. Since the barrier gets influenced with different choice of nuclear interaction potential, here two Skyrme forces (SIII and SSk) are used, which cover a range of barrier characteristics. Further, the fission cross-sections are obtained using SIII and SSk Skyrme forces. Besides, the competition between fission and quasi-fission (QF) events has been observed in terms of cross-sections for $^{31}\text{Al}+^{197}\text{Au}$ and $^{19}\text{F}+^{209}\text{Bi}$ reactions, forming the same CN $^{228}\text{U}^*$. The results obtained are compared with the corresponding experimental data [? ?]. In the fission dynamics of $^{31}\text{Al}+^{197}\text{Au}\rightarrow^{228}\text{U}^*$ reaction, the disintegration of the formed nuclear entity into possible binary fragments can be explored in terms of $V(\eta)$ and P_0 , as shown in panels (a) and (b) of Fig. 6.10, respectively. The analysis described above is performed using the SIII and SSk Skyrme forces at $E_{\text{c.m.}}=106.2, 124.2$ and 163.2 MeV, corresponding to energies near, above, and far away the interaction barrier, respectively. In Fig. 6.10(a), for both the forces, the minima of $V(\eta)$ falls mainly in the asymmetric region, where $\eta_Z = \frac{|Z_1-Z_2|}{Z_1+Z_2} \neq 0$, belonging to $Z_2=31-45$ range. Important to note that, due to the lower barrier height of SSk from that of SIII Skyrme force (see Fig. 6.9), the magnitude of $V(\eta)$ is relatively lower for the former case. The analysis holds true for all the incident energies. Further, it would be interesting to investigate the corresponding influence in the calculation of preformation

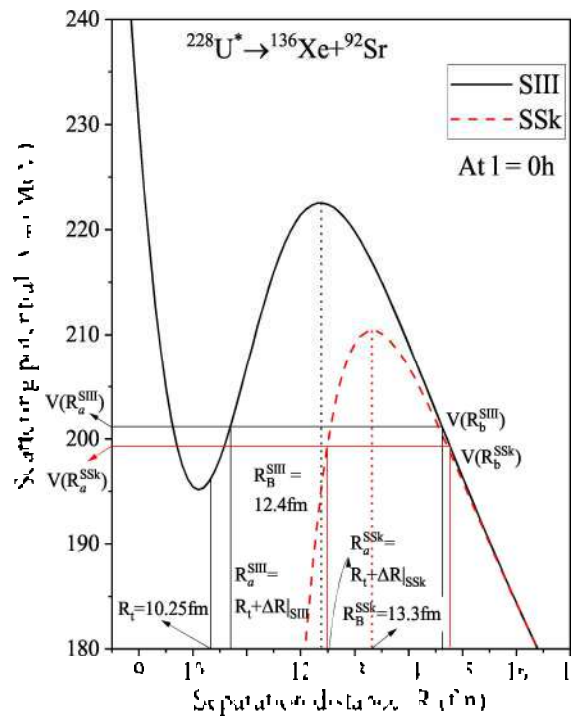


Figure 6.9: The scattering potential V_T (MeV) varying as a function of separation distance R (fm) between the centers of two emitting fragments derived using two Skyrme forces, i.e. SIII and SSk, is shown here for exit channel ($^{228}\text{U}^* \rightarrow ^{136}\text{Xe} + ^{92}\text{Sr}$).

probability (P_0), which shows inverse trend from that of $V(\eta)$.

On the basis of above analysis, in Fig. 6.10(b), the charge distribution of $^{228}\text{U}^*$ CN is shown in terms of the preformation probability $P_0(\eta_Z)$ with respect to the charge number Z_2 of decaying nuclear partners. The structure of $P_0(\eta_Z)$ is basically an inverse trend of $V(\eta_Z)$, thus one can see two peaks of fission fragments in the asymmetric region, i.e. $Z_2 = \frac{Z_{\text{CN}}}{2} \pm 15$ (and $Z_1 = Z_{\text{CN}} - Z_2$; see Eq.(2.50)), here Z_{CN} , Z_1 and Z_2 are the charge numbers of compound nucleus, fragment 1 and fragment 2, respectively. The above results remain similar for both the considered Skyrme forces over a wide range of excitation energies. However, at the highest value of E_{CN}^* ($= 87.8$ MeV), there is a rise of another peak for $Z_2 = 27-30$. The reason behind this analysis will be discussed in Fig. 6.12.

Important to mention that, in Fig. 6.10, the minimization of $V(\eta)$ and P_o has been done in reference to the charge number Z_2 of the decaying nuclear partner from $^{228}\text{U}^*$. In other words, for each Z_2 (varying from 0 to 92), there are isotopes of different mass number, and consequently, for specific mass number A_2 corresponding to Z_2 , there is

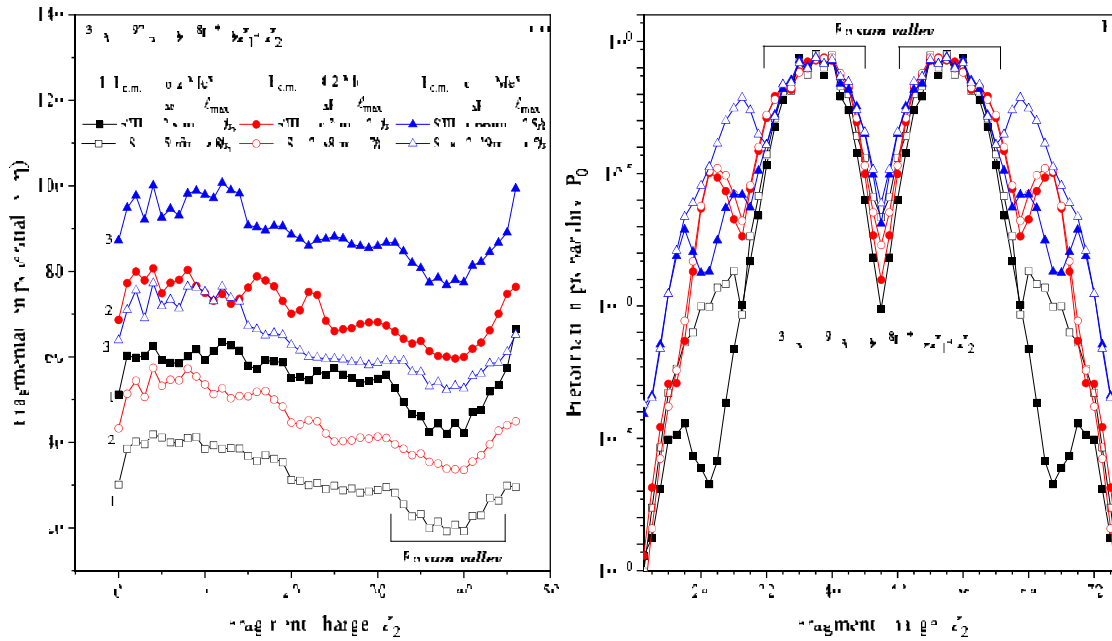


Figure 6.10: (a) The minimized fragmentation potential $V(\eta_Z)$ is shown as a function of Z_2 of the decaying fragment from $^{228}\text{U}^*$ nucleus at energies $E_{c.m.} = 106.2, 124.2$ and 163.2 MeV. (b) The preformation probability $P_0(\eta_Z)$ obtained for preformed fragments (Z_1, Z_2) within excited CN is shown as function of Z_2 , at the above said energies.

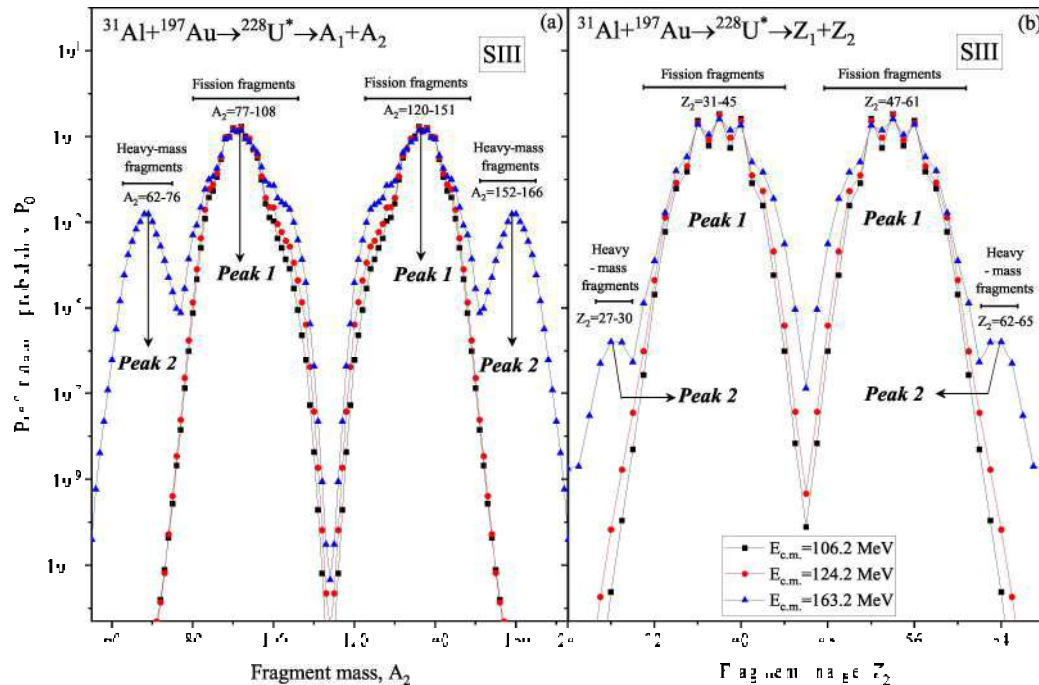


Figure 6.11: (a) The mass and (b) charge distributions of excited compound nucleus $^{228}\text{U}^*$, formed via $^{31}\text{Al} + ^{197}\text{Au}$ reaction at different values of $E_{c.m.}$, are shown in terms of preformation probability P_0 as a function of mass A_2 and charge number Z_2 of decaying fragment, respectively

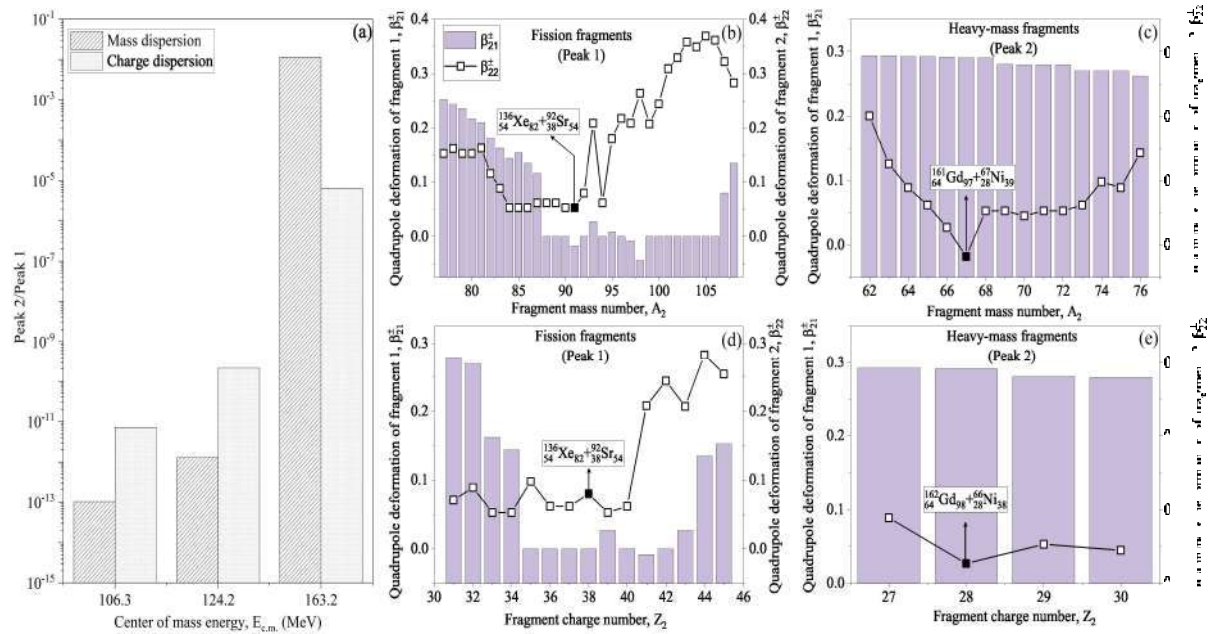


Figure 6.12: (a) The peak ratio (Peak 2/Peak 1) is shown for the most probable fragments appearing in the fission and heavy mass regions of the mass and charge distributions, at $E_{c.m.}=106.3, 124.2$ and 163.2 MeV. The upper [(b) and (c)] and lower panels [(d) and (e)] show the quadrupole deformation β_{2i} (here, $i=1, 2$ correspond to fragment 1 and fragment 2, respectively) of decaying fragments in the fission and heavy mass regions with respect to fragment mass number A_2 and charge number Z_2 , respectively.

a minimum value of $V(\eta)$. For details, one can also go through Ref. [?]. The above method is called as the charge distribution or charge dispersion case. On the other hand, the minimization of fragmentation potential exercised in reference to the mass number of decaying fragment helps in choosing the corresponding charge number. The present work deals with both mass and charge dispersion. The analysis of $^{228}\text{U}^*$ CN over a wide range of incident energies, is shown in Fig. 6.11. Figure 6.11 shows the P_0 depending on η_A and η_Z parameters, with the use of SIII force. The structure of P_0 obtained from both the mass and charge dispersion are very much similar to each other and also in agreement with the earlier study for lower energy range [?]. Additionally, for sake of comparison, I have found in Refs.[? ? ?] that, the authors have determined the percentage yields experimentally for compound nuclei of even-even mass range $A_{CN} = 218 - 230$. In results, symmetric to asymmetric distribution has been noticed as one goes from lighter ($A_{CN} = 218 - 224$) to heavy mas ($A_{CN} = 226 - 230$) nuclei. Also, the asymmetric fission distribution of heavy mass nuclei does not change, even at higher excitation energies. The asymmetric fission region shown in panels (a) and (b) of Fig. 6.11 belongs to $A_2=72-108$

and $Z_2=31-45$, respectively, for all the incident energies. As noticed in Fig. 6.10(b) of the charge dispersion case for highest energy, i.e. $E_{c.m.}=163.2$ MeV, there is a rise in peak of P_0 for $Z_2=27-30$. Similar results have been observed in the mass dispersion case as well, see Fig. 6.11(a).

To understand the reason behind the rise of peak of heavy mass fragments [$A_2=62-76$ & $Z_2=27-30$] in Fig. 6.11, the ratio of **Peak 2** (corresponding to heavy-mass fragments) and **Peak 1** (corresponding to fission fragments), as shown in Fig. 6.6(a) for $E_{c.m.}=106.2$, 124.2 and 163.2 MeV. It is clear from this figure that, the magnitude of **Peak 1** remains prominent for the above said incident energies. However, the most relevant effect of **Peak 2** can be observed at the higher energies. In the explanation of this analysis, the quadrupole deformation ($\beta_{\lambda i}$; here $i=1, 2$ related to fragment 1 and fragment 2, respectively) of decaying nuclear partners belonging to the heavy-mass and fission regions is plotted. See panels (b) and (c) of Fig. 6.12 for mass dispersion case and panels (d) and (e) of Fig. 6.12 for charge dispersion case. In the fission region of either case, the exit channel $^{136}_{54}\text{Xe}_{82}$ ($\beta_{21} = 0.0$) + $^{92}_{38}\text{Sr}_{54}$ ($\beta_{22} = 0.08$) with magic neutron number (for ^{136}Xe), having higher binding energy and hence decay probability from the compound nuclear system. This result holds true independent of the choice of center of mass energies. On the other hand, in the heavy-mass region, the fragments $^{161}_{64}\text{Gd}_{97}$ ($\beta_{21} = 0.290$) + $^{67}_{28}\text{Ni}_{39}$ ($\beta_{22} = -0.018$) and $^{162}_{64}\text{Gd}_{98}$ ($\beta_{21} = 0.291$) + $^{66}_{28}\text{Ni}_{38}$ ($\beta_{22} = 0.027$) decaying through the mass and charge dispersion cases, respectively, are found in the vicinity of the deformed shell-closure effects, for reference see Refs.[? ? ?]. However, the binding energy of these fragments is relatively lower than the most probable fission fragments, i.e. $^{136}\text{Xe}+^{92}\text{Sr}$. On the expense of external energy ($E_{c.m.}$), the heavy mass fragments start appearing at the higher value of center of mass energy, as noticed in terms of preformation probability P_0 in Fig. 6.11.

Also, to calculated the percentage yield (in the fission region) for $^{228}\text{U}^*$ compound nucleus using the relation [?] as a function of decaying fragment charge number Z_2 of compound nucleus, i.e. $^{228}\text{U}^*$. The calculation has been done at excitation energy, i.e. $E_{\text{CN}}^* = 11.0$ MeV, as shown in Fig. 6.13. The charge dispersion of the above said CN has both the asymmetric and symmetric fission peaks, however, the earlier one is more prominent. Such

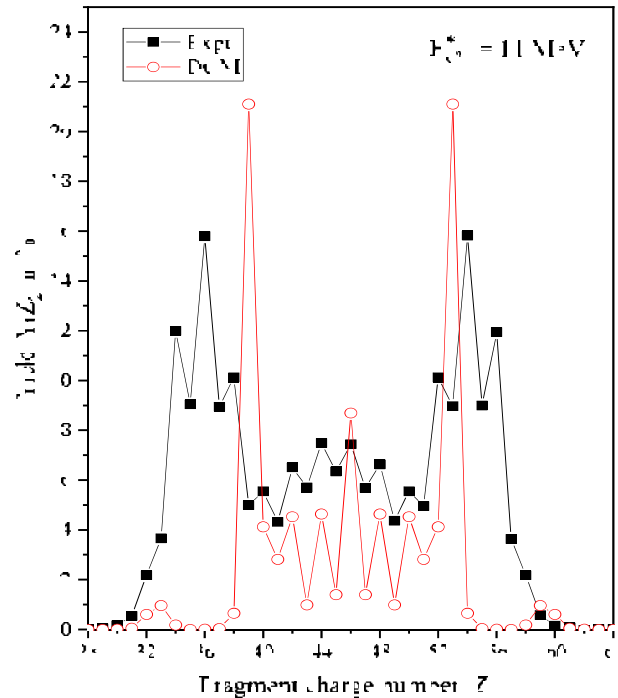


Figure 6.13: A comparison between experimentally and theoretically calculated using DCM percentage yields (Y (in %)) shown as a function of decaying fragment charge number Z_2 of $^{228}\text{U}^*$ at excitation energy, $E_{\text{CN}}^* = 11$ MeV.

behavior of $Y(Z_2)$ obtained theoretically by considering the cold-elongated orientation (as the excitation energy is very low) is found in agreement with the experimental data [?] provided for compound nucleus mass number $A_{\text{CN}} = 228$. Important to mention that, the nuclei with nucleons of magic number and possessing shell-closure effects are the most probable fragments to emit out of the excited Compound Nucleus. Therefore, such decaying nuclear partners have high peaks of yield distribution. For better understanding, in Fig. 6.13, the fragments corresponding to the peak are $^{131}_{53}\text{I}_{78}$ ($\beta_{21} = -0.079$) and $^{97}_{39}\text{Y}_{58}$ ($\beta_{22} = 0.359$). These deformed fragments are located in the vicinity of a deformed magic shell closure. Subsequently, it influences the preformation probability, and thereby affecting the observed yield peak. Also, there could be another reason behind such behavior that, in literature [? ? ?], there are different ways to calculate yields depending on the choice of models/theoretical formalism, though the outcomes obtained are similar barring few uncertainties.

In addition to the above analysis, it is worth noticing that the identification of the fission fragments through both the mass and charge dispersion cases may impart useful insight

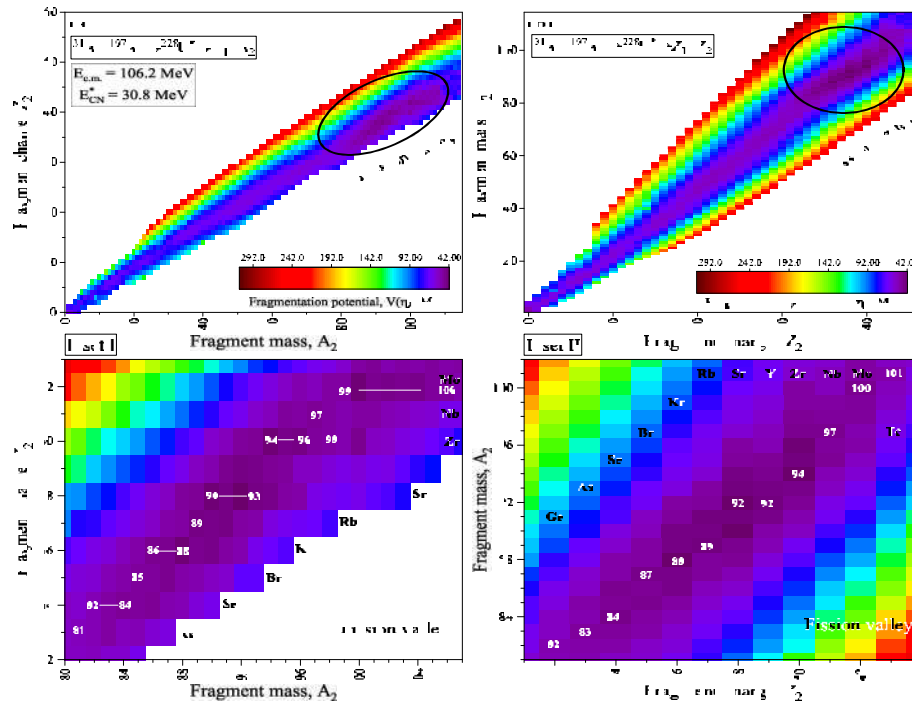


Figure 6.14: (Color online) Heat maps of fragmentation potential $V(\eta)$ (MeV) for (a) mass and charge distribution of $^{31}\text{Al}+^{197}\text{Au}$ reaction, at $E_{c.m.}=106.2$ MeV. Note that, $V(\eta)$ is obtained using SIII Skyrme force.

of the dynamics involved. The newly discovered nuclei can be further explored to enhance the fundamental understanding of various nuclear properties, with potential applications spanning radiation physics, astrophysics, and medical and health-related technologies. In view of this, the identification of decaying nuclear partners has been understood through the heat maps of $V(\eta)$, minimized in reference to the A and Z of fragments, as shown respectively in panels (a) and (b) of Fig. 6.14. The above analysis is done for SIII force parameters. The fission valley is marked in the figures and its zoom version is shown in the insets I and II of Fig. 6.14. In these insets, the mass numbers and corresponding elements, which possess minimum fragmentation potential and fall in the dark purple region are labelled. In Inset I, one may notice that, there is a abundance of isotopes which have same charge number, but different mass number. On the other hand, in Inset II, there are certain isobars (same mass number, but different charge numbers) decaying from excited CN. Such theoretical analysis would help the future experiments to understand the disintegration mechanism followed by the excited compound nuclear system. In addition to the above, the intention is to analyze whether for a particular distribution

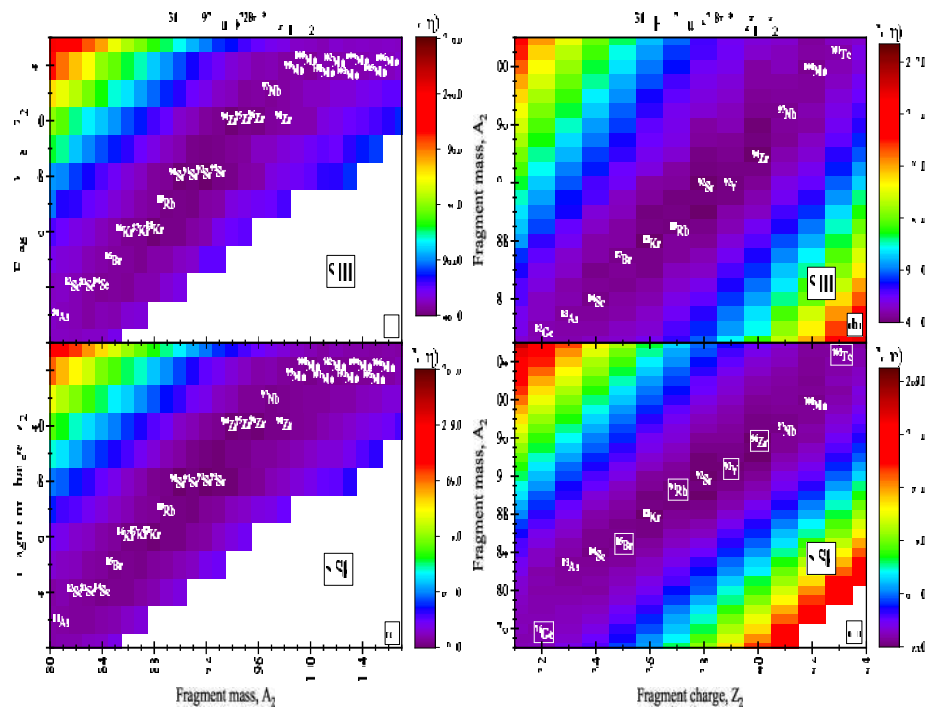


Figure 6.15: (Color online) Same as Fig.6.14, but for (a), (b) SIII and (c), (d) SSk Skyrme forces.

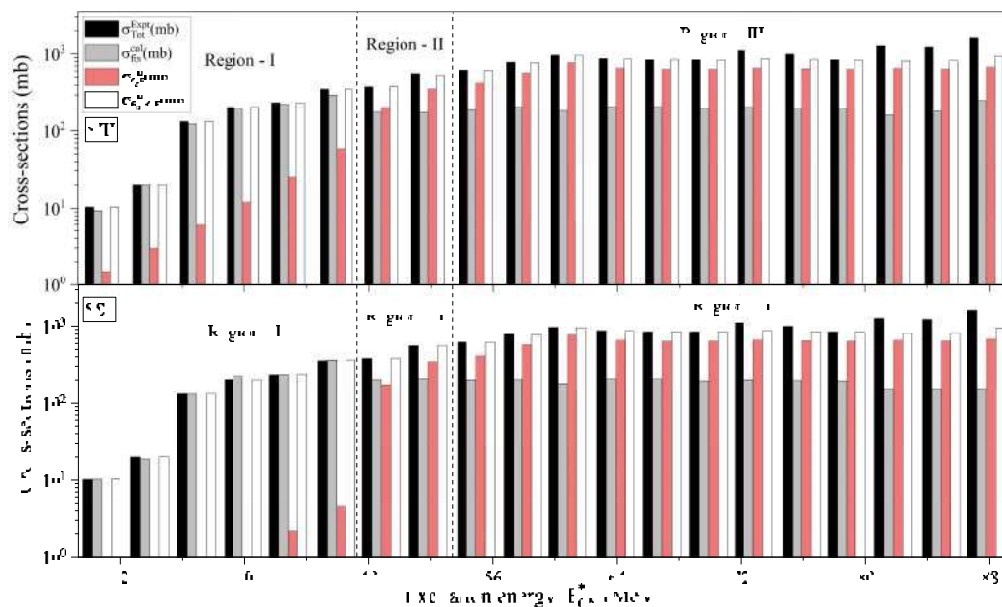


Figure 6.16: The fission (σ_{fis}) and quasi-fission cross-sections (σ_{QF}) calculated as a function of excitation energy E_{CN}^* (MeV), using SIII (upper panel) and SSk (lower panel) Skyrme forces, are shown in comparison with the available experimental data for $^{31}\text{Al} + ^{197}\text{Au} \rightarrow ^{228}\text{U}^* \rightarrow Z_1 + Z_2$ reaction. In both the panels, the Region - I, II and III correspond to the dominance of fission process, competition between fission and QF events and dominance of QF , respectively.

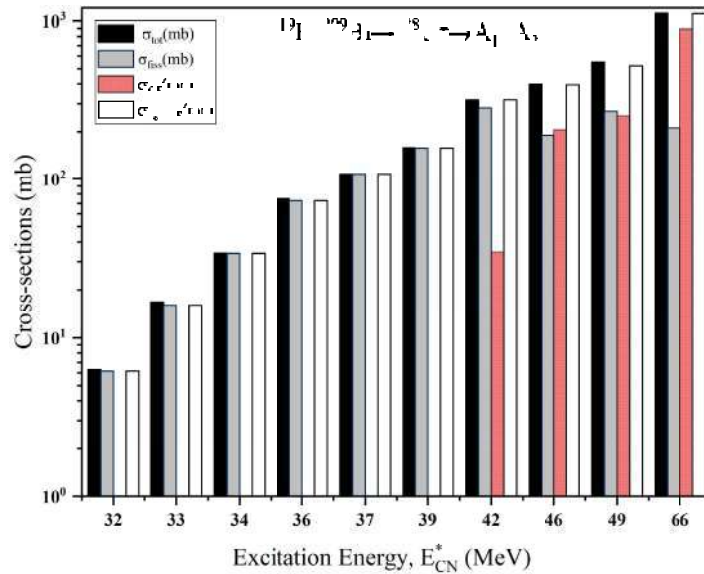


Figure 6.17: Same as Fig. 6.16, but for $^{19}\text{F} + ^{209}\text{Bi} \rightarrow ^{228}\text{U}^* \rightarrow A_1 + A_2$ reaction using SIII force only.

the emitted fragments are identical or not, with the change in nuclear potential. In view of this, heating maps of $V(\eta)$, minimized in reference to the mass and charge numbers of decaying nuclear partner, with the use of SIII and SSk Skyrme forces, are shown in Fig. 6.15. In the mass dispersion case, one can see that the decaying fragments (labelled in the figure) falling in the dark purple region are identical for the considered choice of the Skyrme forces, i.e. SIII and SSk, see panels (a) and (c) of Fig. 6.15. In contrast to this, there is modification in the mass numbers of decaying fragment, as one goes from SIII to SSk force, see panels (b) and (d) of Fig. 6.15. The nuclear potential of Eq.(2.60) depends on the nuclear radius term $[R_i = R_{0i}(1 + \beta_{2i}Y_{2i}^{(0)})]$; here $R_{0i} \propto A_i$, which in turn is a function of mass number of fragment. Therefore, for each A_2 , one will have same value of $V_N(R)$. On the other hand, in the charge dispersion case, for every Z_2 , there is a different choice of A_2 as per the minimization process, henceforth there is modification in the mass numbers of decaying fragments for two different choices of Skyrme forces. From above analysis, it has been noticed that, $^{136}_{54}\text{Xe}_{82} + ^{92}_{38}\text{Sr}_{54}$ possesses the highest preformation probability and minimum value of $V(\eta)$. Either of the fragment having magic number of nucleons (neutron/proton) and spherical shape possesses highest binding energy, and subsequently decay with the largest possibility.

From the above analysis of fission dynamics, the fission cross-sections within the framework

of DCM are calculated for $^{31}\text{Al} + ^{197}\text{Au}$ reaction. Fig. 6.16 shows the cross-sections varying as a function of excitation energy E_{CN}^* ($= E_{\text{c.m.}} + Q_{\text{in}}$; here Q_{in} is the Q -value of the incoming channel) for the above mentioned reaction. Theoretically, the fission cross-sections ($\sigma_{\text{fis}}^{\text{Theo}}$) obtained for the possible fission fragments decaying from $^{228}\text{U}^*$ compound nucleus, formed via above mentioned reaction, using SIII and SSk Skyrme forces are compared with the available experimental data [?]. Here, one may notice that, the grey bar of $\sigma_{\text{fis}}^{\text{Theo}}$ is comparable with the black bar of $\sigma_{\text{fis}}^{\text{Expt}}$ for $E_{\text{CN}}^* < 48$ MeV. On the other hand, for $E_{\text{CN}}^* > 48$ MeV, there is a significant difference between the $\sigma_{\text{fis}}^{\text{Theo}}$ and $\sigma_{\text{fis}}^{\text{Expt}}$ values of fission cross-sections, independent of the choice of Skyrme force. Important to note that, the heavy-mass fragments whose presence becomes significant at the higher values of $E_{\text{c.m.}}$ (see Fig. 6.11) have also been accounted in the calculations of fission cross-sections. The difference observed among the theoretical and experimental results for incident energies of region II and III, shown in Fig. 6.16, suggests the possibility of some competing decay channel. As said in the earlier studies [? ?], the product of considered projectile-target charge number around or greater than 800 may result in possible occurrence of nCN reaction, e.g. QF process.

In view of above, the competition of fission and QF events for $^{19}\text{F} + ^{209}\text{Bi}$ reaction, forming the same CN $^{228}\text{U}^*$, in terms of cross-sections calculated using SIII Skyrme force within DCM are studied. In Fig. 6.17, the cross-sections varying as a function of E_{CN}^* are shown for the above-mentioned reaction and are compared with available experimental data [?]. In this figure, one may notice that, the grey bar of fission cross-sections $\sigma_{\text{fis}}^{\text{Theo}}$ is comparable with the black bar of experimental cross-section $\sigma_{\text{fis}}^{\text{Expt}}$ for $E_{\text{CN}}^* < 42.42$ MeV. On the other hand, for $E_{\text{CN}}^* > 42.42$ MeV, there is a significant difference between the $\sigma_{\text{fis}}^{\text{Theo}}$ and $\sigma_{\text{fis}}^{\text{Expt}}$ values of fission cross-sections. These outcomes consistently align with earlier observations for $^{31}\text{Al} + ^{197}\text{Au}$ reaction and demonstrate the occurrence of nCN reactions at higher energies.

The chosen reaction channels $^{31}\text{Al} + ^{197}\text{Au}$ and $^{19}\text{F} + ^{209}\text{Bi}$, leading to the formation of $^{228}\text{U}^*$ compound nucleus (CN) for incident energies above the barrier, may also proceed via nCN process such as QF . The content of QF cross-section is shown as orange bars in Figs. 6.16 and 6.17. In other words, one can summarize the above results as: (i) the

dominance of fission process for near barrier energies, (ii) competition between fission and QF events for above barrier energies, and (iii) dominance of QF event for energies far away from the Coulomb barrier.

6.3 Summary

The spontaneous binary and ternary fission of ^{252}Cf is studied using a theoretical approach based on QMFT. Firstly, the binary fragmentation potential of ^{252}Cf is calculated by employing the two types of nuclear potentials. One with the proximity and the other with SEDF-based potential. The different potentials significantly modify the structure and magnitude of the fragmentation potential. Consequently, the deepest minima in the fragmentation potential, which indicate the most probable fragments, vary depending on the potential used. The calculations using the SEDF approach (SKT3 force) demonstrate a reasonable agreement with experimental half-lives, validating the choice of nuclear potential. The mass distribution of spherical configuration leads to nearly symmetric fragments (^{122}Cd ($Z=48$, $N=74$) + ^{130}Sn ($Z=50$, $N=80$)) due to the presence of spherical shell closure effects. Whereas in cold-elongated configurations, fragments (^{108}Mo ($Z=42$, $N=86$) + ^{144}Ba ($Z=56$, $N=88$)) with high deformations and large mass asymmetry start playing their role. Furthermore, the SKT3 force is employed to investigate the ternary fission process in the decay of the ^{252}Cf nucleus. The analysis focuses on the equatorial cluster tripartition, where the third fragment is fixed ($A_3 = {}^4\text{He}$). The three-body fragmentation potential is calculated by considering spherical and deformed choices of decaying fragments. The scattering potential of most probable fragments reveals that the emission of deformed fragments is more likely. Therefore, the relative yield for the ternary fission of the ^{252}Cf nucleus is calculated for the deformed case and compared with experimental data.

In addition to this, the decay dynamics of compound nuclear system, i.e. $^{228}\text{U}^*$, formed via $^{31}\text{Al} + ^{197}\text{Au}$ reaction within the framework of DCM is studied. The most probable fission fragments of $^{228}\text{U}^*$ CN appearing in the asymmetric region have neutron magic configuration, and hence result in higher binding energy/ stability. This result holds true for all ($E_{\text{c.m.}}$), lying across the Coulomb barrier. Beside this, the heavy-mass fragments (HMFs), i.e., $^{161}_{64}\text{Gd}_{97}$ ($\beta_{21} = 0.290$) + $^{67}_{28}\text{Ni}_{39}$ ($\beta_{22} = -0.018$) [and $^{162}_{64}\text{Gd}_{98}$ ($\beta_{21} = 0.291$) +

$^{66}_{28}\text{Ni}_{38}$ ($\beta_{22} = 0.027$) are appearing in the vicinity of deformed shell-closure effects but have relatively smaller B.E. than that of fission fragments. Such HMFs peak become significant at higher energies in mass as well as charge dispersion case.

Additionally, in the calculation of fission cross-sections for $^{31}\text{Al}+^{197}\text{Au}$ entrance channel over incident energies $E_{\text{c.m.}}=106.2\text{-}163.2$ MeV, the quasi-fission QF (nCN) event starts competing with the fission (CN) process for $E_{\text{c.m.}} \sim 124$ MeV (or $E_{\text{CN}}^* > 48$ MeV). Similarly analysis has also been observed for another choice of projectile-target combination (i.e. $^{19}\text{F} + ^{209}\text{Bi}$), forming the same CN ($^{228}\text{U}^*$). Important to mention, the above result is independent of the choice of Skyrme forces, i.e. SIII and SSk, although they modify the barrier significantly.

The overall outcome of the present work, along with the major conclusions derived from the systematic investigations carried out, is concisely summarized in the final chapter.

CHAPTER 7

SUMMARY

In the present investigation, binary, ternary and quaternary fission, are examined by incorporating various nuclear structure effects such as deformation, orientation, and configuration-dependent considerations (ECT and CCT). These factors play a crucial role in determining the potential energy surface and consequently influence the most probable fragmentation channels. The binary and ternary decay analyses are performed within the frameworks of the preformed cluster model (PCM) and the three-cluster model (TCM), respectively, both of which are formulated under QMFT. Furthermore, the formalism is extended to include the quaternary fission mode to explore the emission dynamics involving four fragments simultaneously, thereby providing a more comprehensive understanding of complex fission phenomena.

Hence, using PCM the investigation of binary decay (α , CR, HPR and SF) is carried out for nuclei in the atomic number range $Z=89-102$. The α -decay $\log T_{1/2}$ is calculated for two sets of chosen nuclei by fitting neck length parameter (ΔR). The obtained ΔR is further used to calculate Q-value dependent first turning point i.e. $R_a(Q)$. The $R_a^\alpha(Q)$ relations are employed to calculate α decay half-lives of the nuclei with in chosen range and found to be in good agreement with the experimental data. The calculated P_o decreases with increase in the A (mass number) of parent nuclei. This may be associated with corresponding enhancement in P_o of fissioning region. After the α decay analysis, the $R_a(Q)$ relations are obtained for CR and HPR decay modes. Further, a comparative analysis of α -decay and SF is made using the fragmentation potential and preformation distribution. Additionally, investigation of single α , simultaneous 2α , and heavier cluster decays has been carried out within for Ac and Th isotopes using the PCM. The study

encompasses a broad range of isotopes, $^{207-229}\text{Ac}$ and $^{210-230}\text{Th}$ systematically analyzing their decay characteristics through the computation of Q-values, preformation factors, barrier penetrabilities, and half-lives. Among various nuclear interaction potentials considered, the Modified Prox 88 potential was found to yield the most consistent results, and was therefore adopted for the comprehensive decay analysis. The decay systematics across these isotopes reveal an evolution in decay behavior: while α decay remains the dominant mode throughout, the 2α emission channel becomes comparatively more favorable in lighter isotopes. In contrast, heavier cluster decay, particularly ^{14}C emission is found to be more prominent in isotopes with higher neutron numbers. This trend aligns well with existing experimental observations, where the cluster radioactivity is predominantly reported in heavier isotopes. The computed half-lives demonstrate that isotopes such as ^{219}Ac and ^{220}Th are especially favorable for 2α emission, exhibiting the lowest decay half-lives for this mode. Additionally, significant even-odd staggering is observed in both half-lives and preformation factors, underscoring the sensitivity of decay processes to nuclear pairing and shell effects. The Geiger-Nuttall plots for both α and 2α emissions show strong linear correlations, reaffirming the quantum tunneling nature of these decay modes.

In addition to binary fission, the spontaneous ternary fission of ^{252}Cf is studied within TCM. For both (binary and ternary), the fragmentation potential is computed by including β_2 deformations. For both decay modes, the fission fragment mass distribution shifts from a symmetric distribution to an asymmetric one when transitioning from the optimum hot-compact configuration to the cold-elongated configuration. This behaviour arises due to the reduction in the interaction radius of decaying fragments as the system transitions from cold-elongated to the hot-compact configuration. The β_2 deformed compact/ 90° - $90^\circ/0^\circ$ - $90^\circ/90^\circ$ - 0° configuration shows the dominance of symmetric and near symmetric decay channels with prominent influence of spherical magic shell closure. However, for elongated/ 0° - 0° orientation (β_2 deformed) approach shows asymmetric distribution with the dominance of deformed magic shell closure. Further, ECT to CCT configurations are studied by considering $A_3 = ^{30}\text{Mg}$ and ^{48}Ca . It is concluded that the deformations and orientations play a significant role in identifying the binary and ternary fission fragments.

Hence, various orientation prospects are explored which may impart useful insights for future understanding of reaction dynamics on theoretical as well as experimental front. After the detailed exploration of binary and ternary fission processes, attention is now directed toward the phenomenon of multicluster emission, which encompasses quaternary fission. The study of multicluster fission is of considerable significance, as it bridges the understanding between conventional fission modes and highly complex fragmentation mechanisms. To do a comprehensive analyses, initially, the binary fragmentation potential is employed and ^4He , ^{46}Ar , ^{82}Ge and ^{116}Pd are identified as most probable fragments along with their complementary fragments. In the next step, the ternary fission analysis of ^{252}Cf nucleus is made by keeping ^4He , ^{46}Ar and ^{82}Ge as fixed third fragments. It is observed that the magnitude and structure changes significantly as one moves from a lighter to a heavier third fragment. The identified minima in the fragmentation potential are attributed to the presence of shell closure. After the identification of the most probable two and three-fragment combinations, the quaternary fission analysis has been made. A comparison of all probable arrangements for collinear configuration in quaternary fission is worked out, and the one arrangement with elongated neck between two heavy fragments is found as most probable. In the light fragment-accompanied quaternary fission modes, $(A_1, \alpha, \alpha, A_2)$ and (A_1, α, t, A_2) are found as most probable cases.

After studying light fragment emission, an attempt is made to explore the heavy fragment emission mechanism. It is observed that the fragmentation structure varies significantly with an increase in the mass of the third and fourth fragments. A secondary dip is observed when the mass of the third fragment becomes $\sim 25\%$ and $\sim 13\%$ of the parent for ternary and quaternary fission, respectively. The fragment combinations of ternary and quaternary fission along the fission axis are identified. The suggested combinations in reference to ternary decay include $^{48-52}\text{Ca}$ nuclei along with $^{68-74}\text{Ni}$ and $^{129-133}\text{Sn}$ isotopes. Which is in alignment with the available experimental data. Similarly, ^{34}Si , ^{46}Ar , and $^{48-52}\text{Ca}$ have been identified as third and fourth ($A_3'' = A_4''$) fragments in the quaternary fission. The experimental verification of these will be of future interest. Further, the relative yield and fragmentation potential are analysed as a function of fragment mass for two distinct choices of surface separation ($s=0$ fm and $s=1$ fm). The results indicate that

the overall behaviour of yield is in consistent with the fragmentation structure.

In order to understand the influence of the different combinations of the middle fragments on the fragmentation potential, the combinations of light fragments such as ^1H , ^2H , ^3H , ^4He , ^6Li , and ^8Be are considered. The study further explores heavier clusters such as ^{10}Be and ^{14}C , reinforcing the significance of shell effects and energy minimization in the dynamics of multicluster emissions. Finally, the analysis of ternary and quaternary fission are performed with particular emphasis on surface separation effect by adopting two geometrical configurations (collinear and equatorial). For ternary fission, calculations show that the most probable fragment combinations ^{132}Sn ($Z = 50, N = 82$) + ^4He ($Z = 2, N = 2$) + ^{116}Pd ($Z = 46, N = 70$) are independent of surface separation, although there is significant difference in the magnitude of fragmentation potential, particularly at higher separation distance. In addition, the quaternary fission analysis is performed for both equatorial and collinear configurations, considering various light charged particles as middle fragments.

To further elucidate the influence of nuclear interaction potentials on the fission dynamics, a systematic comparison has been carried out by employing two distinct forms of the nuclear potential. Firstly, the binary fragmentation potential of ^{252}Cf is calculated by employing the two types of nuclear potentials. One with the proximity and the other with SEDF-based potential. The different potentials significantly modify the structure and magnitude of the fragmentation potential. Consequently, the deepest minima in the fragmentation potential, which indicate the most probable fragments, vary depending on the potential used. The calculations using the SEDF approach (SKT3 force) demonstrate a reasonable agreement with experimental half-lives, validating the choice of nuclear potential. The mass distribution of spherical configuration leads to nearly symmetric fragments (^{122}Cd ($Z=48, N=74$) + ^{130}Sn ($Z=50, N=80$)) due to the presence of spherical shell closure effects. Whereas in cold-elongated configurations, fragments (^{108}Mo ($Z=42, N=86$) + ^{144}Ba ($Z=56, N=88$)) with high deformations and large mass asymmetry start playing their role. Furthermore, the SKT3 force is employed to investigate the ternary fission process in the decay of the ^{252}Cf nucleus. The analysis focuses on the equatorial cluster tripartition, where the third fragment is fixed ($A_3 = ^4\text{He}$). The three-body fragmentation potential

is calculated by considering spherical and deformed choices of decaying fragments. The scattering potential of most probable fragments reveals that the emission of deformed fragments is more likely. Therefore, the relative yield for the ternary fission of the ^{252}Cf nucleus is calculated for the deformed case and compared with experimental data.

In addition to this, the decay dynamics of compound nuclear system, i.e. $^{228}\text{U}^*$, formed via $^{31}\text{Al}+^{197}\text{Au}$ reaction within the framework of DCM is studied. The most probable fission fragments of $^{228}\text{U}^*$ CN appearing in the asymmetric region have neutron magic configuration, and hence result in higher binding energy/ stability. This result holds true for all ($E_{\text{c.m.}}$), lying across the Coulomb barrier. Beside this, the heavy-mass fragments (HMFs), i.e., $^{161}_{64}\text{Gd}_{97}$ ($\beta_{21} = 0.290$) + $^{67}_{28}\text{Ni}_{39}$ ($\beta_{22} = -0.018$) [and $^{162}_{64}\text{Gd}_{98}$ ($\beta_{21} = 0.291$) + $^{66}_{28}\text{Ni}_{38}$ ($\beta_{22} = 0.027$)] are appearing in the vicinity of deformed shell-closure effects but have relatively smaller B.E. than that of fission fragments. Such HMFs peak become significant at higher energies in mass as well as charge dispersion case.

Additionally, in the calculation of fission cross-sections for $^{31}\text{Al}+^{197}\text{Au}$ entrance channel over incident energies $E_{\text{c.m.}}=106.2\text{-}163.2$ MeV, the quasi-fission QF (nCN) event starts competing with the fission (CN) process for $E_{\text{c.m.}} \sim 124$ MeV (or $E_{\text{CN}}^* > 48$ MeV). Similarly analysis has also been observed for another choice of projectile-target combination (i.e. $^{19}\text{F} + ^{209}\text{Bi}$), forming the same CN ($^{228}\text{U}^*$). Important to mention, the above result is independent of the choice of Skyrme forces, i.e. SIII and SSk, although they modify the barrier significantly.

FUTURE SCOPE

In the present work, binary, ternary, and quaternary fission processes have been systematically investigated. Nuclear deformation effects have been incorporated in the binary and ternary fission channels by considering quadrupole (β_2) deformations of the interacting fragments. The scope of the present study may be further broadened in several significant directions. Extension of this work involves the inclusion of higher-order multipole deformations, such as octupole (β_3) and hexadecapole (β_4) components, particularly in the analysis of binary and ternary fission processes. This incorporation is expected to play an important role in determining the fine structure of fragmentation potentials and barrier profiles. In addition, deformation effects can be explicitly included in the quaternary fission framework, where the presence of an additional fragment and more complex geometric arrangements may significantly enhance shape polarization and mutual orientation effects. The influence of such higher-order deformations on fragmentation potentials, barrier characteristics, preformation probabilities, penetrabilities, and decay half-lives can be systematically examined.

Furthermore, the present analysis has been confined to spontaneous binary, ternary, and quaternary decay modes. An important and physically relevant extension would be the investigation of induced multicluster emission processes, wherein the fission event is initiated by external probes such as neutrons. The study of induced ternary fission, in particular, would enable a detailed assessment of the role of excitation energy, angular momentum transfer, and nuclear temperature on fragmentation structure, barrier dynamics, and decay probabilities. By incorporating excitation-energy-dependent potentials, temperature-dependent shell corrections, and rotational effects into the existing theoretical framework, a more comprehensive and realistic description of fragment mass distributions, total kinetic energies, and emission probabilities under induced fission conditions can be achieved. Such an extension would significantly enhance the understanding of multicluster emission dynamics and the evolution of nuclear structure effects in excited compound systems.