

**DECAY PATTERNS AND RELATED
DYNAMICAL ASPECTS
OF SUPERHEAVY NUCLEAR SYSTEMS**

A THESIS

Submitted in the partial fulfillment of the requirement
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DOCTOR OF PHILOSOPHY

under the guidance of

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by

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With God's Grace
as
All of me is a part of Him

CERTIFICATE

This is to certify that the thesis entitled “**DECAY PATTERNS AND RELATED DYNAMICAL ASPECTS OF SUPERHEAVY NUCLEAR SYSTEMS**” being submitted by **Gurjit Kaur** for the fulfillment of the requirements for the award of Degree of Doctor of Philosophy in the School of Physics and Materials Science, Thapar Institute of Engineering and Technology, Patiala, is a record of the candidate’s own work carried out by her under my supervision. The matter presented in this thesis has not been submitted in part or full for the award of any degree in any university or institute.

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“Challenges are what make life interesting and overcoming them is what makes life meaningful. Just accept the challenges and have fun”

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Contents

Abstract	1
1 Introduction	7
1.1 SHE-An island born out of nuclear structure	9
1.2 Production mechanisms of SHN	11
1.2.1 Hot and cold fusion mechanisms	12
1.2.2 Synthesis of nuclei with $Z>118$	15
1.3 Description of decay patterns	16
1.3.1 Non-compound nucleus processes	17
1.3.2 Compound nucleus processes	18
1.4 Role of deformations and orientations	19
1.5 Motivation behind the present work	21
1.6 Delineation of the Thesis	22
Bibliography	25
2 Methodology	33
2.1 Introduction	33
2.2 Description of some preliminary expression used in methodology . . .	35
2.3 The Fragmentation Potential Energy (V)	38
2.3.1 Binding Energies (B_i)	39
2.3.2 The Coulomb Potential (V_C)	41
2.3.3 Rotational or Centrifugal Potential (V_ℓ)	42
2.3.4 The Nuclear Proximity Potential (V_N)	44
2.4 Fusion Model based on Wong approach	47
2.4.1 Capture or total cross-section:	47
2.4.2 Fusion cross-section:	49
2.5 Decay dynamics using collective clusterization approach	50
2.5.1 Preformation Probability (P_0)	53
2.5.2 Penetrability or Tunneling Probability (P)	53
2.5.3 Decay Cross-sections	55
Bibliography	56

3	Analysis of neutron evaporation in superheavy mass region	63
3.1	Introduction	63
3.2	Calculations and Results	66
3.2.1	Dynamics of $1n$ emission in Pb and Bi induced reactions . . .	67
3.2.2	Evaporation residue cross-sections of $^{267}\text{Db}^*$ nucleus	80
3.3	Conclusions	82
	Bibliography	83
4	Fission dynamics of various even mass superheavy nuclei	87
4.1	Introduction	87
4.2	Calculations and Results	90
4.2.1	Fission and TKE analysis of ^{48}Ca -induced reactions	91
4.2.2	Effect of optimum orientations on the fission dynamics of ^{238}U - induced reactions	105
4.3	Conclusions	114
	Bibliography	115
5	Capture and fission analysis of various odd mass superheavy iso- topes	119
5.1	Introduction	120
5.2	Calculations and Results	123
5.2.1	Dynamics of Db isotopes in ^{238}U , ^{248}Cm , and ^{249}Bk induced reactions	124
5.2.2	Production of $Z=107-111$ superheavy nuclei via hot fusion re- actions	133
5.3	Conclusions	144
	Bibliography	146
6	Influence of higher order deformations on fusion dynamics	151
6.1	Introduction	152
6.2	Calculations and results	155
6.3	Conclusions	170
	Bibliography	172
7	Summary and Conclusions	175

List of Tables

3.1	Catalogue of cold fusion reactions probed in experiments at different laboratories. The reactions are organised as per Z of compound nucleus and Coulomb parameter $z=Z_1Z_2/(A_1^{1/3}+A_2^{1/3})$. In addition to this, the Coulomb barrier and maximum value of center-of-mass energy ($E_{c.m.}$) are also reported.	64
3.2	DCM calculated fission barrier heights (B_f) and neutron separation energies (S_{1n}) for $Z_{CN}=104-113$ nuclei, formed in ^{208}Pb and ^{209}Bi -induced cold fusion reactions.	67
3.3	Comparison of experimental [8,16–23] and DCM calculated $1n$ cross-sections (σ_{1n}) of $Z_{CN}=104-109$ nuclei, by including spherical as well as deformed choices of fragmentation at $\ell = \ell_{max}$	69
3.4	Target-projectile combinations (A_1, A_2) referring to potential energy minima in Fig. 4 for “hot optimum” orientations of various studied reactions and their characteristic properties at $\ell=\ell_{max}$	73
3.5	DCM fitted $1n$ -cross-sections (σ_{1n}) calculated at maximum excitation energies and compared with experimental data [8,16–23] using sticking moment of inertia (I_S) approach.	76
3.6	Comparison of experimental [29] and DCM calculated $4n$ and $5n$ -decay cross-sections of $^{267}\text{Db}^*$ nuclear system by including sticking (I_S) and non-sticking (I_{NS}) moment of inertia.	80
4.1	The DCM calculated fusion-fission (σ_{FF}) and asymmetric quasi-fission (σ_{QFasym}) cross-sections for the decay of compound systems $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ formed in $^{48}\text{Ca}+^{238}\text{U}$, $^{48}\text{Ca}+^{244}\text{Pu}$, and $^{48}\text{Ca}+^{248}\text{Cm}$ reactions, respectively.	97
4.2	DCM calculated fission ($\sigma_{\frac{A}{2}\pm 20}$) cross-sections for $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}120^*$ nuclei using hot orientation approach and compared with experimentally available data of [16]. The excitation energies, temperature, neck-length parameters, and angular momentum values are also reported.	111

4.3	DCM predicted fission ($\frac{A}{2} \pm 20$) cross-sections for nuclei $Z=104-120$, formed in ^{238}U -induced reactions at Coulomb barrier energies. The mass-asymmetry (η_A), compound nucleus formation probability (P_{CN}), E_{CN}^* , $E_{c.m.}$, and angular momentum are also reported. All the cross-sections are predicted by fixing the adjustable neck-length parameter $\Delta R=1.0$ fm.	113
5.1	DCM fitted fusion-fission cross-sections (σ_{ff}) of $^{265}\text{Db}^*$ and $^{267}\text{Db}^*$ nuclei formed respectively in $^{27}\text{Al}+^{238}\text{U}$ and ($^{19}\text{F}+^{248}\text{Cm}$, $^{18}\text{O}+^{249}\text{Bk}$) reactions by using hot compact configurations. The experimental and theoretical predicted (using Wong model) fusion-fission and capture cross-sections are also shown in Table. The contribution of fusion-fission cross-sections to the capture cross-sections are also tabulated in percentage form.	133
5.2	ℓ -summed Wong calculated Coulomb barrier height (V_B), barrier position (R_B), along with deformations (β_{2i}), Coulomb factor ($Z_P Z_T$), Businaro-Gallone mass asymmetry (α_{BG}), entrance channel mass-asymmetry (η), $ Q $ -value of entrance channel for the synthesis of $Z=107, 109, 110$, and 111 superheavy nuclei.	138
6.1	Target-projectile (t-p) combinations (A_1, A_2) referring to potential energy minima in Fig. 3 for $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ nuclei and their characteristic properties for hot orientations of fragments.	161
6.2	Angles corresponding to compact configuration of reactions with ^{48}Ca as projectile, colliding with ^{237}Np , ^{243}Am , and ^{249}Bk prolate-shaped targets resulting in $^{285}\text{Nh}^*$, $^{291}\text{Mc}^*$, and $^{297}\text{Ts}^*$ compound systems. Further ^{209}Bi induced reactions interacting with ^{50}Ti , ^{54}Cr , ^{58}Fe , ^{64}Ni , and ^{70}Zn projectiles giving odd- Z $^{259}\text{Db}^*$, $^{260}\text{Sg}^*$, $^{267}\text{Mt}^*$, $^{273}\text{Rg}^*$, and $^{279}\text{Nh}^*$ superheavy nuclei.	167
6.3	Generalized form of different configurations measured for various interacting possibilities of nuclei, depending on the magnitude of the β_2 and β_4 deformation parameters.	171

List of Figures

1.1	A theoretical map representing different stable land of nuclei. An island of stability for SHN is also shown around $N=180$ and $Z=120$ [16].	10
1.2	Pictorial representation of hot and cold fusion mechanisms for the synthesis of SHN.	12
1.3	Decay scenario of superheavy elements via different compound and non-compound nucleus decay modes.	17
1.4	Representation of optimum and compact configuration of colliding nuclei based on the magnitude of deformations.	21
2.1	Flow chart representing the systematic of fusion and decay models for the study of SHN.	34
2.2	Schematic representation of (a) non-sticking, (b) rolling, and (c) sticking mode of moment-of-inertia (MOI) for two colliding nuclei.	43
2.3	Explanation of nuclear shapes and associated parameters used in QMFT.	51
2.4	The scattering potential $V(R)$ at $\ell=\ell_{max}$ for the decay of $^{264}\text{Rf}^*$ superheavy nucleus with all the important parameter marked.	54
3.1	Variation of fragmentation potential as a function of light fragment mass for the hot and cold orientations of the fragments, plotted at $\ell = \ell_{max}$ values for (a) $^{258}\text{Rf}^*$ and (b) $^{267}\text{Mt}^*$ nuclei at fixed magnitude of neck-length parameters (ΔR), best fitted for hot orientation approach.	70
3.2	Same as Fig. 3.1, but plotted for preformation probability (P_0) corresponding to the neck-length parameters (ΔR), best fitted for hot optimum orientations.	71
3.3	Mass fragmentation potentials $V(\text{MeV})$, plotted at $\ell=\ell_{max}$ for the formation of $Z_{CN}=104-109$ nuclei corresponding to $E_{CN}^*=15 \pm 1$ MeV, having hot optimum orientations and β_{2i} -deformations included for all possible (t,p)-combinations of incoming nuclei. The experimentally verified (t,p)-combinations are shown in boldface.	74

3.4	(a) Comparison of DCM fitted $1n$ cross-sections with experimental data [8,16–23] and (b) variation of scattering/effective potential with range (R) using sticking moment of inertia (I_S). These figures are shown at the maximum available energies.	78
3.5	Same as Fig. 3.4, but plotted for the non-sticking (I_{NS}) approach of moment of inertia, at maximum reported energies.	79
3.6	Fragmentation potential for $^{267}\text{Db}^*$ nuclear system plotted as a function of light fragment mass A_2 using sticking (I_S) and non-sticking (I_{NS}) limits of moments of inertia.	81
3.7	Variation of the (a) fragmentation potential $V(\text{MeV})$, (b) preformation probability (P_0), and (c) penetration probability (P) for $^{267}\text{Db}^*$ nucleus formed in $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions, plotted as a function of angular momentum for $4n$ and $5n$ decays.	82
4.1	Fragmentation potentials minimized in mass coordinate $\eta(A)$ for the decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei, plotted at excitation energy ~ 39 MeV and for highest value of angular momentum $\ell=\ell_{max}$ using the deformed choice of fragmentation.	92
4.2	Variation of preformation probability with the fragment mass for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ superheavy nuclei, by including the β_{2i} -deformation effects within hot optimum approach, plotted at fixed neck-length parameter and highest value of angular momentum.	94
4.3	Variation of fragmentation potential with the angular momentum for most symmetric fission fragment and Pb-isotopes of asymmetric quasi-fission in the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ nuclei.	95
4.4	Variation of penetration probability with the fragment mass for the decay of $Z=112$, 114 , and 116 superheavy nuclei, by including the β_{2i} -deformation effects within hot optimum approach. Symmetric fission fragments can have fusion-fission and quasi-fission origin. The penetrability of asymmetric quasi-fission fragments are also shown. . .	96
4.5	Preformation probability plotted with the fragment mass for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ superheavy nuclei within the application of different versions of proximity potentials, namely Prox-77, Prox-88, and Prox-00.	98
4.6	$\overline{TK\bar{E}}$ - distribution of the fragments plotted for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, (c) $^{296}116^*$ superheavy nuclei, using hot optimum orientations and β_{2i} -deformations. The calculated $\overline{TK\bar{E}}$ values are plotted for Prox-77, modified Prox-77 and Prox-88 values.	100

4.7	Scattering potential, plotted to observe the TKE (or $\overline{TKE}$)-values with the use of Prox-77, Prox-00 and Prox-88 potentials at the fixed neck-length parameter (ΔR) and maximum value of the angular momentum (ℓ_{max}).	101
4.8	$\overline{TKE}$ -distribution of the $^{286}112^*$ fragments, plotted at extreme values of angular momentum i.e. ℓ_{max} and ℓ_{min} values for Prox-88 potential.	102
4.9	$V(R_a)$ or TKE values given for different radii used in the Prox-88 potential at $\Delta R=0$, plotted at minimum values of angular momentum.	104
4.10	$\overline{TKE}$ -distribution of the fragments, plotted using Prox-88 potential at $\Delta R=0.0$ fm and at minimum value of angular momentum ℓ_{min}	104
4.11	Left panel (hot orientations) and right panel (cold orientations) shows the preformation probability (P_0) as a function of fragment mass (A_i) plotted at near the Coulomb barrier energies for $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}120^*$ nuclei.	106
4.12	Fragmentation potential $V(\eta, R)$ plotted with fragment mass (A_i) for (a) $^{274}\text{Hs}^*$, (b) $^{286}\text{Cn}^*$, (c) $^{286}\text{Fl}^*$, and (d) $^{302}120^*$ nuclei formed via ^{238}U -induced reactions by considering hot and cold orientations of decaying fragments.	108
4.13	Variation of scattering potential as a function of range for spherical, cold, and hot interactions of the fragments.	109
4.14	Variation of the preformation probability as a function of fragment mass for even nuclei (a) $^{264}\text{Rf}^*$ ($Z=104$), (b) $^{268}\text{Sg}^*$ ($Z=106$), (c) $^{274}\text{Hs}^*$ ($Z=108$), (d) $^{278}\text{Ds}^*$ ($Z=110$), (e) $^{286}\text{Cn}^*$ ($Z=112$), (f) $^{286}\text{Fl}^*$ ($Z=114$), (g) $^{290}\text{Lv}^*$ ($Z=116$), (h) $^{296}\text{Og}^*$ ($Z=118$), and (i) $^{302}120^*$ ($Z=120$). The figures are plotted at the excitation energies corresponding to the Coulomb barrier V_C	112
5.1	(a) Fragmentation potential $V(\eta, R)$ plotted with respect to fragment mass for the decay of (a) $^{264}\text{Rf}^*$, (b) $^{265}\text{Db}^*$, and (c) $^{268}\text{Sg}^*$ nuclei formed in the ^{238}U -induced reaction at fixed neck length parameter (ΔR) and angular momentum (ℓ_{max}) values, for static- β_{2i} deformed cases.	124
5.2	Preformation probability (P_0), plotted as a function of fragment mass for the decay of $^{265}\text{Db}^*$ nucleus using (a) hot static-deformed, (b) hot dynamic-deformed, and (c) cold static-deformed approaches. The figures are useful to extract the knowledge about different decay mechanisms and further used to calculate the fusion-fission cross-sections. The inset of Fig. 5.2(c) is same as that of the remaining figures, but plotted for the cold dynamic deformations of the nuclei.	126

5.3	Variation of the (a) Coulomb (V_C), (b) proximity (V_P , Prox-1977), and (c) centrifugal (V_ℓ) potentials for the fragments lying in range $A_2=85-110$, by including the static and dynamic hot deformed configurations, along with static-cold orientations of the decay fragments.	128
5.4	(a) Total interaction potential (V_T) as a function of range (R) for $^{267}\text{Db}^*$ nuclear system formed via two incoming channels <i>i.e.</i> $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$. (b) Barrier heights (V_B) plotted for the above reactions at different excitation energies (E_{CN}^*).	130
5.5	Compound nucleus formation probability (P_{CN}) of $^{267}\text{Db}^*$ nucleus produced via $^{18}\text{O}+^{249}\text{Bk}$ and $^{19}\text{F}+^{248}\text{Cm}$ reactions with E_{CN}^* .	131
5.6	The Wong predicted capture and fusion cross-sections, for the reactions (a) $^{19}\text{F}+^{248}\text{Cm}$ and (b) $^{18}\text{O}+^{249}\text{Bk}$ leading to $^{267}\text{Db}^*$ nuclear system at energies near the Coulomb barrier.	132
5.7	Comparison of experimental (symbols) and theoretically calculated (lines) capture (σ_{Cap}) as well as fusion-fission (σ_{ff}) cross-sections for $Z=104$ to $Z=120$ superheavy nuclei formed in different hot fusion reactions.	135
5.8	The percentage deviation of (a) barrier height (V_B) and barrier radius (R_B) from experimental numbers as a function of the charge product (Z_1Z_2) by taking deformations up to β_2 at “optimum” orientations.	136
5.9	Theoretically predicted capture (σ_{Cap}) and fusion-fission (σ_{ff}) excitation functions for the synthesis of (a,b) $Z=107$, (c,d) $Z=109$, (e,f) $Z=110$, and (g,h) $Z=111$ superheavy nuclei. The respective ℓ -values are also shown in the inset of figures.	139
5.10	Variation of capture and fusion-fission cross-sections for $Z=107$ as a function of excitation energy (E_{CN}^*) for (a) $^{24}\text{Mg}+^{243}\text{Am}$ (b) $^{48}\text{Ti}+^{210}\text{At}$ reactions.	141
5.11	Compound nucleus formation probabilities (P_{CN}) plotted as a function of excitation energy (E_{CN}^*) for $Z=107$, 109 , 110 , and 111 superheavy nuclei formed via different entrance channels.	142
5.12	Variation of capture cross-section at each target angle (θ_T) for $^{24}\text{Mg}+^{243}\text{Am}$ reaction at energy near the Coulomb barrier ($E_{CN}^*=52$ MeV).	143
5.13	Variation of fission barrier heights (B_f) and neutron separation energy (B_n) as a function of compound nucleus fissility parameter (x_{CN}) for $Z=107$, 109 , 110 , and 111 superheavy nuclei.	144

6.1	Variation of barrier height (V_B) as a function of orientation angle (θ) for (a) β_2 and $\beta_2+\beta_4$ deformed nucleus at $T = 0$ MeV and $\ell = 0\hbar$ and (b) effect of angular momentum states on the barrier height with fixed magnitude of temperature, $T=1.25$ MeV.	156
6.2	Barrier height (V_B) plotted with orientation angle (θ) for $^{209}\text{Bi}+^{70}\text{Zn}$ reaction, using β_2 and $\beta_2+ \beta_4$ deformations.	158
6.3	Mass fragmentation potential ($V(\text{MeV})$) for the formation of (a) $^{279}\text{Nh}^*$ nucleus using cold orientations (b) $^{279}\text{Nh}^*$ nuclear systems using hot configuration of the fragments and (c) hot orientations applied to $^{285}\text{Nh}^*$ nucleus, corresponding to $T=0$ MeV and $\ell= 0\hbar$, calculated at $R=R_B$. The minima(s) in mass fragmentation potential give various (t-p) combinations for $^{279}\text{Nh}^*$ and $^{285}\text{Nh}^*$ nuclei.	159
6.4	Distribution of barrier height (V_B) with orientation degree of freedom for deformed nuclear system $^{285}\text{Nh}^*$ by considering pure (a) quadrupole (β_2) (b) octupole (β_3) and (c) hexadecupole (β_4) deformations.	163
6.5	Variation of barrier height (V_B) as a function of orientation angle (θ) for $^{285}\text{Nh}^*$ nucleus having (a) different quadrupole deformations at $\beta_3=0$ and $\beta_4=0.102$ (b) different octupole deformations in addition to $\beta_2=0.215$ and $\beta_4=0.102$ (c) different hexadecupole deformations for fix $\beta_2=0.215$, with negligible magnitude of β_3 -deformation parameter.	165
6.6	Comparison of compact behavior of two different reactions, i.e. $^{209}\text{Bi} + ^{70}\text{Zn}$ and $^{208}\text{Pb} + ^{73}\text{Ga}$ having comparable magnitude of β_2 and β_4 (for target nuclei) but of opposite signs and same signs of deformations respectively. Barrier height for reaction $^{208}\text{Pb} + ^{73}\text{Ga}$ is plotted on right vertical scale (open circles) and for $^{209}\text{Bi} + ^{70}\text{Zn}$ is plotted on left vertical scale (filled circles).	169

Abstract

The theoretical and experimental interpretation of decay patterns and related aspects of superheavy nuclei have attracted prodigious attention which in turn leads to the motivation for obtaining utmost conditions for the synthesis of stable nuclei in the extreme mass region of periodic table. The theoretical study of superheavy nuclei (SHN) is undertaken in this thesis. The compound and non compound nucleus disintegration mechanisms of SHN are investigated and the results are compared with the experimental data, where ever available. The relevance of incident energy, entrance channel effects, angular momentum, Coulomb factor, deformations and orientations have been explored in view of different decay channels and some new predictions are suggested for the future validation. The analysis is presented in seven chapters and chapter-wise description is given below.

Chapter 1 provides the information about the origin of superheavy nuclei, their island of stability, and production techniques (hot and cold fusion mechanisms) to synthesize these elements. Furtherance to this, an interpretation of different excited state decay mechanisms operating in this mass region is discussed in brief. Beside this, the impact of deformations and orientations in view of the dynamics involved is outlined along with the motivation and applicability of the work compiled in this thesis.

Chapter 2 present the mathematical structure of fusion and decay models employed to inquest the superheavy dynamics. A brief description of some input parameters used in the methodology is provided in the beginning followed by the explanation of different constituents of fragmentation potential *i.e.* binding energies, Coulomb potential, proximity potential, and angular momentum dependent potential. By considering these input parameters, the fusion (Wong and ℓ -summed Wong model) and decay (Dynamical Cluster Decay model (DCM)) models are appropriately elaborated. The fusion models are employed to extract the information

about capture and fusion events and, a method to calculate the capture and fusion cross-sections in term of angular momentum partial waves is discussed in this chapter. Dynamical Cluster Decay model (DCM), established from Quantum Mechanical Fragmentation Theory (QMFT), is used to study the decay mechanisms of compound systems formed in heavy ion induced reactions. In order to estimate the mass-distributions of decaying fragments, the preformation probability (P_0) is formalized using η -dependant Schrödinger wave equation. The WKB approximation method used to estimate the barrier penetrability (P) is also discussed. It is relevant to mention that the deformations and orientations effects are duly incorporated in both type of models. A descriptive analysis of work done within this methodology is elaborated in chapters 3 to 6 and concluded in chapter 7.

Starting with the neutron evaporation study, in **Chapter 3**, the $1n$ evaporation cross-sections (σ_{1n}) of cold fusion reactions (Pb and Bi targets) are calculated for $Z_{CN}=104-113$ superheavy nuclei. The calculations are carried out at the excitation energy $E_{CN}^*=15\pm 1$ MeV using sticking moment of inertia (I_S), so that the comparative analysis of reaction dynamics be worked out. First of all, the fission barriers (B_f) and neutron separation energies (S_{1n}) are estimated to account the cross-sections of cold fusion reactions. In addition to this, the importance of hot optimum orientations of β_{2i} -deformed nuclei over cold one is explored at fixed angular momentum and neck-length parameter. The hot optimum orientations support the target-projectile (t,p) combinations, which are explored experimentally. Some new target-projectile combinations are also predicted for future exploration. Further, the $1n$ cross-sections are addressed for $Z_{CN}=104-113$ superheavy nuclei at given excitation energies which show the decent agreement with experimental data upto $Z_{CN}=111$. To understand the dynamics of higher-Z superheavy nuclei, the effect of non-sticking moment of inertia (I_{NS}) is also investigated. Finally, the role of sticking (I_S) and non-sticking (I_{NS}) moments of inertia is also analyzed for the $4n$ and $5n$ channels of $^{267}\text{Db}^*$ nuclear system.

The literature survey suggest that the fission processes are the main obstacle to the formation of stable evaporation residues, so a detailed analysis of fission processes is carried out in **Chapter 4**. The dynamics of $^{48}\text{Ca} + (^{238}\text{U}, ^{244}\text{Pu}, ^{248}\text{Cm})$ reactions is studied at comparable excitation energies across the Coulomb barrier. To understand the capture stage of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei, the compound nucleus formation probability is calculated. The indication of $P_{CN} < 1$ demonstrates the fact that some competing process such as quasi-fission may occur at the capture stage of ^{48}Ca induced reactions. For further apprehension, the comparative decay analysis of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei is carried out using β_{2i} -deformations within hot optimum orientation criteria and the fission cross-sections are estimated which find nice agreement with the available data. The fission mass distribution show a double humped structure where peak observed around Sn-region looks to find its genesis in symmetric quasi-fission component. On the other hand, the emergence of peaks around Lead (Pb) in the decay of $Z=112$, 114 , and 116 nuclei signify the possible presence of asymmetric quasi-fission. Higher and broader asymmetric quasi-fission peaks are observed for $^{296}116^*$ and $^{292}114^*$ nuclei as compared to $^{286}112^*$ nucleus. Beside this, the TKE-distribution of the decay fragments is also explored by using different proximity potentials, such as Prox-77, Prox-88, and Prox-00. The Prox-88 seems to perform better and the calculated TKE-values find relatively better comparison at lower angular momentum states. The possible role of different radii of the decaying fragments is also exercised to understand the $\overline{TKE}$ -dynamics of $^{48}\text{Ca} + ^{238}\text{U}, ^{244}\text{Pu}, ^{248}\text{Cm}$ reactions.

In extension to above, the fission mass distribution of $Z=104-120$ superheavy nuclei formed in ^{238}U -induced reactions is investigated. The cross-section of symmetric fragments (with masses $\frac{A}{2} \pm 20$ of $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}120^*$ nuclei) are calculated over a wide energy spectrum by rationalizing the neck-length parameter (ΔR). The calculations are carried out by employing the hot and cold optimum orientation approaches. Within hot orientation criteria, symmetric fission distribu-

tion is observed for $^{274}\text{Hs}^*$ nucleus which becomes highly asymmetric in nature for $^{302}120^*$ compound system. The Pb-peaks originating due to quasi-fission process start competing while going from $^{274}\text{Hs}^*$ to $^{302}120^*$ nucleus. Additionally, the role of cold orientation approach is also explored for these nuclei which show the opposite trend in the mass distribution while going from $Z=108$ to $Z=120$ superheavy system.

The role of temperature dependent deformations on the decay path is studied in **Chapter 5**. The fission analysis of some least explored superheavy nuclei is also carried out in this chapter. **Chapter 5** is devoted to investigate the decay of $^{265}\text{Db}^*$ and $^{267}\text{Db}^*$ nuclei, formed in the $^{27}\text{Al}+^{238}\text{U}$, $^{18}\text{O}+^{249}\text{Bk}$, and $^{19}\text{F}+^{248}\text{Cm}$ hot fusion reactions via DCM and Wong models at energies around the Coulomb barrier. First, the fission dynamics of $^{27}\text{Al}+^{238}\text{U}$ reaction is explored by investigating the fragmentation and preformation yield of the reaction. The symmetric mass distribution of the fission fragments is observed for $^{265}\text{Db}^*$ nucleus, when static β_{2i} -deformations are used within hot optimum orientation approach. However, the mass split gets broaden for the use of β_{2i} -dynamical (T-dependent) hot configuration of the fragments and becomes clearly asymmetric for cold-static deformed approach. Within the application of cold orientations of fragments, a new fission channel is observed at mass asymmetry $\eta=0.29$. In addition to ^{238}U -induced reaction, the work is carried out to address the fission and neutron evaporation cross-sections of $^{267}\text{Db}^*$ nucleus formed via $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions, besides a comprehensive analysis of fusion and capture processes. Higher fusion cross-sections and compound nucleus formation probabilities (P_{CN}) are obtained for $^{18}\text{O}+^{249}\text{Bk}$ reaction, as a consequence of reduced Coulomb factor.

Further, the capture and fission analysis of heavy ion induced fusion reactions leading to the formation of $Z=107-111$ superheavy nuclei has been carried out. Attempts have been made to analyze the synthesis traits such as excitation functions, formation probabilities, barrier characteristics *etc.* The ℓ -summed Wong model gives reasonable description of available data on capture (σ_{Cap}) and fusion-fission (σ_{ff})

cross-sections and hence is exploited to make relevant predictions for future experiments. The capture and fusion-fission excitation functions are predicted for least explored region of superheavy nuclei (SHN) i.e. $Z=107-111$. The role of mass-asymmetry (η), Coulomb factor ($Z_P Z_T$), deformation and orientations, Businar-Gallone mass-asymmetry (α_{BG}), fission barrier (B_f) *etc* is duly explored. Present study conclude that, the mass-asymmetric reactions involving ^{24}Mg , ^{30}Si , and ^{36}S projectiles are preferred for the synthesis of new isotopes of $Z=107-111$. Alternatively, the doubly magic ^{48}Ca -projectile provides a competing alternate to produce neutron rich isotopes of above mentioned SHN.

In **Chapter 6**, the role of higher order deformations (β_3 and β_4) is analyzed on the superheavy reaction dynamics. Using the extended fragmentation theory, the compactness of hot and cold fusion reactions is analyzed for odd- Z nuclei ranging $Z=105-117$. The calculations for the present work are carried out at $T=0$ MeV and $\ell=0\hbar$, as the temperature and angular momentum effects remain silent while addressing the orientation degree of freedom (i.e. compact angle configuration). In hot fusion (^{48}Ca (spherical)+ actinide (prolate)) reactions, the non equatorial compact (nec) shape is obtained for $Z=113$ nucleus. On the other hand, $Z>113$ nuclei favor equatorial compact (ec) configuration. The distribution of barrier height (V_B) illustrate that the ec-shape is obtained when the magnitude of quadrupole deformation of the nucleus is higher than the hexadecupole deformation. In other words, negligible or small -ve β_4 -deformations support ec configurations. On the other hand, large (+ve) magnitude of the β_4 -deformation suggests that the compact configuration appears for compact angle $\theta_c < 90^\circ$, leading to nec structure. Similar deformation effects are observed for Bi-induced reactions, in which not belly to belly compact (nbbc) configurations are seen at $\theta_c=42^\circ$. In addition to the effect of β_2 and β_4 -deformations, the exclusive role of octupole deformations (β_3) is also analyzed. Finally it is emphasized that β_3 -deformations do not follow the reflection symmetry as that of β_2 and β_4 , leading to the possible occurrence of compact configuration

within 0^0 to 180^0 angular range.

Lastly, **Chapter 7** compile the results and discussions obtained, and presents the summary of this work along with the future prospective for possible extension.

Chapter 1

Introduction

The microscopic nuclear world which act as a baseline for the creation of universe, is of immense curiosity since the detection of nucleus inside an atom. The knowledge of background discoveries are of extreme importance for the elucidation of nuclear physics. These discoveries are interconnected so rigorously that sometimes it becomes difficult to decide their hierarchy. The revelation of the X-rays by Wilhelm Conrad Röntgen in 1895 [1] intensified the forage of modern nuclear physics. Consecutively, Henri Becquerel discovered the radioactivity in 1896 [2] and gave an intensive sight about this field. Due to the restrained understanding of nuclear behavior, this discipline was limited mainly to academic and research interest until 1930s. The 2nd global warfare became the climacteric event of this field due to its implication in fighting tools. The day to day advancement in this field have attracted huge attention in view of its utilization in nuclear power, nuclear medicine, radiocarbon dating, archaeology, nuclear engineering *etc.*

A momentous event in this subject was the detection of neutron inside the core in 1932 [3] and soon after, efforts were continued to have a better insight of atomic nucleus and its properties. Even after a period of 100 years from the origin of nuclear physics, the detailed description of nucleus is far from complete knowledge because of complex behavior of nuclear forces. Now a day physicists inspect the various kinds of nuclear reactions and nuclear structure phenomena which are helping a lot to

understand the field. This knowledge has cardinal prominence in the production of artificial nuclei, energy generation in stellar interior, and in the hunt for superheavy elements (SHE). The well known speculation of the atomic and nuclear physics about the existence of atom is that the electron revolve around the charge center up to a limit $Z \leq 170$ and hence heavy atoms can exist up to the same. But the stability zone is much below this threshold due to increase in Coulomb repulsion and corresponding uncertainty in the nucleonic composition. The exploration of the peculiarities belonging to new elements have become the most important field of nuclear physics after the discovery of first artificial element Neptunium (Np) in 1940 [4]. This search simulated the investigation of nuclei at the stability lines in the territory of heaviest masses, which are regulated by the vanishing of fission barriers [5, 6]. As the production of new superheavy elements is a difficult task due to the arduous structural properties, so various theories and models have been developed to understand the associated reaction peculiarities. The liquid drop model (LDM) given by N. Bohr and J. A. Wheeler [7] not only describes atomic masses, binding energies, α and β decay modes accurately but it also provides a base line for the validation of magic numbers of a nucleus. In 1949, M. G. Mayer [8] and D. Jensen [9] introduced the concept of shell structure and explained the nuclear magic numbers. It was anticipated that the “magic” numbers of protons and neutrons inside a nucleus correspond to relatively elevated binding energies in their ground states. This fact is explained in shell model as a testimony of the nuclear structure similar to that of closed electron shells in the atomic structures [8–10]. Based on the concept of shell-corrections, a stable land named “island of stability” was forecasted by G. T. Seaborg [11] for the existence of superheavy nuclei (SHN). This prophecy has encouraged the search of new nuclei making use of heavy-ion fusion reactions and the production of elements upto $Z=118$ [12–17] suggest the possibility of superheavy magic land near $Z=114, 120, 126$ and $N=184$ shell closure [18–22].

The intricate nature of SHN makes their analysis much interesting and hence

SECTION 1.1: SHE-AN ISLAND BORN OUT OF NUCLEAR STRUCTURE

attracts much focus. For the better perception of these nuclei, there is a need of deep assimilation of the associated nuclear properties. The main peculiarities of these elements are: (i) they are short lived nuclei, having half-life time of few seconds and hence are very sensitive to fission and other decay modes, (ii) due to the scarcity of these in nature, they are synthesised artificially in laboratories, (iii) these are classified as extremely radioactive nuclei, and (iv) shell stabilization energy results in enhanced fission barrier which owe their existence. Here, an attempt is made to address the various aspects of SHN in the subsequent sections.

1.1 SHE-An island born out of nuclear structure

To understand the features of SHN explained above, the macroscopic (LDM) and microscopic (shell effects) models were exploited extensively. This macroscopic point of view was explained by N. Bohr and J. A. Wheeler [7] with the assumption that nucleus behaves like a macroscopically structureless body (like charged liquid drop) due to the saturation properties and low compressibility. The shape of the nucleus is described by the balance between surface tension and Coulomb repulsive force which changes with the addition of protons and neutrons. The counter action of these forces brings forth the fission of nucleus into two fragments at some critical point, which is defined as fission barrier (LDM barrier). With increasing atomic number, the Coulomb force competes with the binding energy and this LDM barrier starts vanishing which sets the limit for the production of heavy elements. The nuclei far off this limit (*i.e.* $Z > 100$) are unstable and decay via spontaneous fission (SF) mode with $T_{1/2} < 10^{-16}$ sec [23]. Quite unexpectedly, numerous nuclei far off this limit survive and decay via α or β emission with half-lives upto several seconds. A detailed analysis of theoretical and experimental data of nuclear masses has shown that the deviation of experimental binding energies from the theoretical one has a regular trend and are largest at definite magic numbers of protons and neutrons. The reason of this discrepancy lies in the fact that non-uniformities in

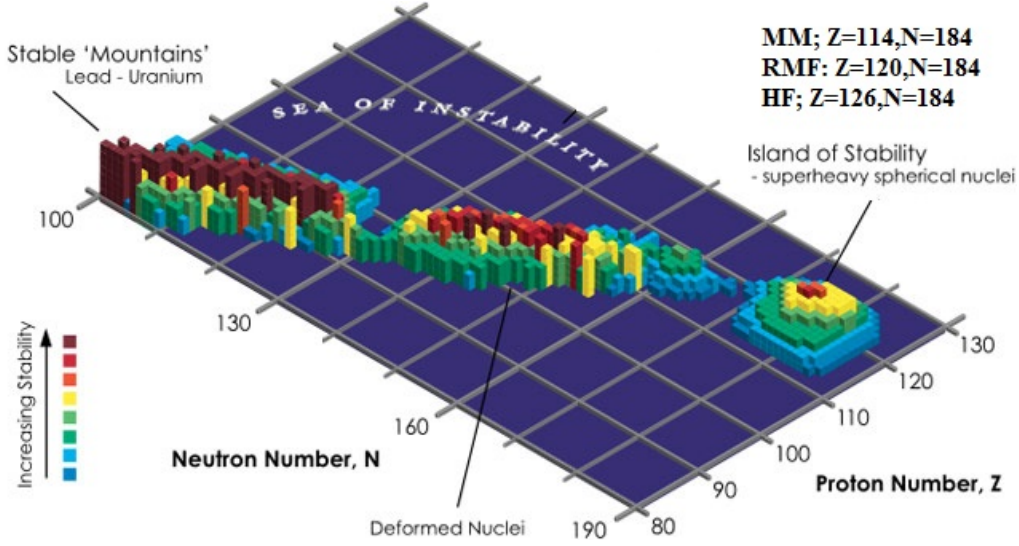


Figure 1.1: A theoretical map representing different stable land of nuclei. An island of stability for SHN is also shown around $N=180$ and $Z=120$ [16].

the distribution of nucleons are not considered by the macroscopic approach, which leads to the concept of shell-correction [9, 10]. Shell-corrections or shell effects play crucial part in the appraisal of SHN and provide additional fission barrier to survive against fission. On the basis of this, macro-microscopic (MM) theory was proposed by Strutinsky [24] according to which the potential energy surfaces are calculated by using the energy $E = E_{macro} + E_{micro}$, with E_{macro} as liquid drop energy and E_{micro} as shell correction energy [23, 25, 26].

The fickleness in the estimation of nuclear shell effects do not influence the universal inference about the existence of “island of stability”, but substantially changes the limit of endure of nuclei. Before this, the first region of stability appeared around the isotopes of Thorium ($Z=90$) and Uranium ($Z=92$) whose lifetimes are comparable to the age of universe. This stability land is separated from stable Pb ($Z=82$) and Bi ($Z=83$) region by unstable elements. Encouraging from this it is expected that the second region of stability also exist around $Z=114$, 120 , or 126 and neutron number $N=184$ [18–22]. A map showing the stable land of Uranium (U) isolated from predicted stable superheavy land is manifested in Fig. 1.1. Note that the neu-

tron magic ($N=184$) for superheavy is well established but proton magic ($Z=114$, 120, and 126) is not fixed yet. Without going into much details in this way, for superheavy nuclei, based on different parameters, different theories were developed to predict the proposed magic numbers. Earlier macro-microscopic models were developed in which the shell closure were predicted at $N=184$ and $Z=114$ [18, 19]. Also relativistic mean field (RMF) model has predicted $Z=120$ and $N=184$ as next magic shell closure [20, 22]. Another purely microscopic self-consistent approach is the Skyrme Hartree Fock approximation (uses Skyrme and Gogny forces) which predicted the significant increase in binding energies around $Z=120$ and 126 with $N=184$ [21]. Although, the $Z=114$ nuclei don't show the stability as per predictions, however one may expect to get superheavy magicity near $Z=120$ or $Z=126$. After a brief discussion on the existence of superheavy nuclei, their synthesis techniques are elaborated in the next section.

1.2 Production mechanisms of SHN

In the first conviction about the possible production of SHN in 1964, the limit on fusion was not foreseen and all the available nuclei were amalgamated with each other on the way to synthesize new elements. It took over two decades to understand that production by fusion is a limited factor. Step by step the production process was understood and eventually we reached upto $Z=118$ element by fusing stabilized collision partners in heavy-ion induced reactions. The fusion of heavy nuclear systems is hindered as compared to that of light nuclear systems and the cross sections for such synthesis comes out to be extremely small. So, as to minimize the hinderance in fusion, it is sensible to select the optimal projectile-target for the production of a stable superheavy nucleus [27]. In accordance to the theoretical research, the experimentalists have ventured for the search of land of stability. Highly modified and proficient techniques have been designed to synthesize the neutron and proton rich superheavy nuclei. In view of this, heavy ion reactions were considered

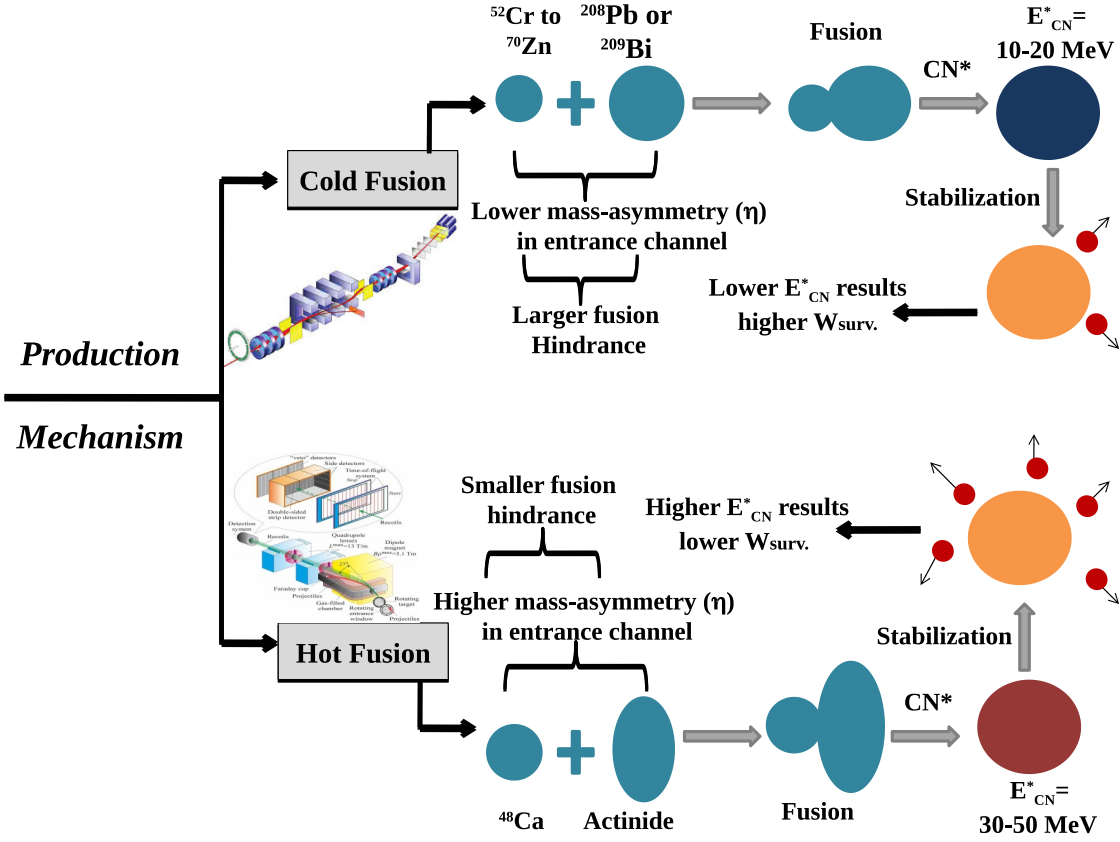


Figure 1.2: Pictorial representation of hot and cold fusion mechanisms for the synthesis of SHN.

as the required probe and are intensively investigated both experimentally as well as theoretically [12–17]. The two different fusion techniques named as cold fusion and hot fusion (categorized in Fig. 1.2) have been used and corresponding production criteria is elaborated in the subsequent subsection.

1.2.1 Hot and cold fusion mechanisms

Earlier, the actinide targets such as Uranium (U) to Californium (Cf) with projectiles varying from Boron (B) to Oxygen (O) were used for the formation of super-heavy nuclei. Such kind of interaction generates the hot CN with excitation energy (E_{CN}^*) 30-70 MeV that stabilizes with the decay of 3-5 neutrons. With increasing the projectile-target mass (hence Coulomb energy), E_{CN}^* of compound nucleus increases

SECTION 1.2: PRODUCTION MECHANISMS OF SHN

which is liable for the fallout of survival probability of evaporation residue and shell effects [27,28]. These factors limit the superheavy elements up to 106. Due to small production probability with increased atomic number, modification was required to produce higher superheavy elements and hence cold fusion process was adopted.

In cold fusion mechanism, doubly magic ^{208}Pb and ^{209}Bi targets are taken with projectiles from Cr to Zn. Within this process, the compound nucleus with higher survival probability is produced, because the disintegration of CN generally takes place via evaporation of 1 or 2 neutrons and gamma rays, at low E_{CN}^* in the range of 10-20 MeV [29,30]. In addition to neutron evaporation, the fusion-fission (FF) and quasi-fission (QF) analysis is also of much interest (the detail of the phenomena are explained later in Sec 1.3). Using cold fusion mechanism, symmetric yield of the decay fragments is obtained for lighter superheavy nuclei. Due to symmetrical distribution, the dominance of the fusion-fission (FF) or compound nuclear fission (CNF) process can be anticipated. Conversely, the contribution of non-compound nucleus (nCN) decay, such as QF is less because quasi-fission process is governed through the asymmetric mass distribution of the decay fragments. Contrary to this, the probability of symmetric distribution decreases and the yield of projectile and target like products gets enhanced significantly with increasing mass in cold fusion reactions. For further heavier systems, QF and deep-inelastic scattering are dominant processes due to reduced mass-asymmetry and increased Coulomb factor (Z_1Z_2) [31–33]. Hence, an important conclusion about the cold fusion reaction can be withdrawn, which lies in the fact that hunting of higher atomic number with this mechanism is not possible due to fusion hindrance caused by decrement of mass asymmetry. Also, the nuclei produced via this fusion reaction contain less number of neutrons. Accordingly, the elements from $Z=107$ to 112 [29, 30] have been synthesized using this technique and then it seems difficult to proceed further for higher Z nuclei with in this synthesis approach.

To overcome the difficulties faced in the cold fusion reactions, relatively asym-

metric hot fusion reactions were proposed by nuclear physicists. For this, instead of light projectiles (e.g. Boron to Oxygen) used earlier (in traditional hot fusion reactions), doubly magic ^{48}Ca [34] was suggested to move towards the island of stability. In this process, the compound nuclei with excitation energy 30-50 MeV are produced. Using this method, elements from 113-118 were synthesized [12–15] and was later tested for the synthesis of lighter superheavy nuclei also. This method is relatively useful due to the following reasons: (i) at this excitation energy range, the shell effect are still prominent and the probability of survival of evaporation product is larger than the earlier process. (ii) the mass asymmetry in entrance channel reduces the suppression of fusion and hence the cross section for CN formation increases. (iii) superheavy nuclei are formed with the neutron excess lying closer to the predicted $N=184$ neutron magic.

In hot fusion reactions, pronounced asymmetric QF and FF processes are also observed in addition to neutron evaporation and their contribution enhances with increment in the mass and charge of nuclei. As for hot fusion reactions, the target nuclei are deformed so the reaction dynamics are notably effected by the deformations and orientations effects. Additionally, the excitation energy of CN also affects the contribution of fusion-fission and QF components. The contribution of fusion-fission is relatively larger at above barrier energies. Further, if the energy is decreased to below barrier range, the symmetric distribution is negligible and major endowment comes from quasi-fission events [31–33]. The reason behind this fact is that, in the above barrier range, the collisions between target and projectile nuclei are equatorial, in which a compact shape of the product is generated which further follows fission as well as QF paths. At the same time, in the below barrier region, polar collisions take place which give rise to the elongated structure of the composite system. Hence the probability of the quasi-fission becomes higher as compared to the fusion-fission process. The comparison among the mass-TKE matrices of hot and cold fusion reactions shows that contribution of QF enhances more firmly in

cold fusion reactions as compared to hot one and convincingly show that hot fusion reactions are more preferable for producing higher mass SHN [35, 36]. Also, the properties of fusion-fission and QF decay processes are interconnected so tightly that the experimental segregation is tough. To achieve the same, numerous techniques like mass distributions, angular distribution, width distribution *etc* have been proposed, which provide useful insight about the understanding of the dynamics of such reaction mechanisms.

These production techniques extend the periodic table upto $Z=118$ and we are slowly gearing towards the predicted superheavy magic land. The hunt to reach this region is very much alive particularly due to modified and advanced techniques, some of which are listed ahead.

1.2.2 Synthesis of nuclei with $Z>118$

On stepping towards the magic land of superheavy elements, the main obstruction is that the nuclei with $Z>118$ cannot be amalgamated using ^{48}Ca -based reactions since ^{249}Cf is the heaviest available target nucleus. A possible alternative is to use the projectiles heavier than ^{48}Ca such as ^{58}Fe , ^{64}Ni , and ^{54}Cr with suitable actinide targets. In the last decade, we have witnessed significant efforts to synthesize the superheavy nuclei beyond $Z=118$ [37–41], but not succeeded as yet to extend the periodic table. Some experimental attempts for synthesis of $Z=119$ and $Z=120$ with projectile heavier than ^{48}Ca are listed below:

1. In 2007, $^{244}\text{Pu} (^{58}\text{Fe}, xn) ^{302-x}120$ was studied using Dubna gas-filled recoil separator (DGFRS) where no decay chain consistent with fusion-evaporation was observed [37].
2. In 2007-08, $^{238}\text{U} + ^{64}\text{Ni}$ reaction giving $^{302-x}120$ was studied at Separator for heavy-ion reaction product (SHIP), GSI. No such event was identified that confirms the existence of the required compound system [38].
3. In 2011, an upper cross-section limit of 0.56 was adjusted in reaction of ^{248}Cm

with ^{54}Cr for production of $^{302}120$ at SHIP. No event from the isotopes of element 120 was observed [39].

4. Two experiments of ^{50}Ti with ^{249}Cf and ^{249}Bk targets were performed at GSI recoil separator TransActinide Separator and Chemistry Apparatus (TASCA) in 2011 and 2012 for synthesis of $Z=120$ and $Z=119$ respectively. Results have not yet been made public [40].

The artificially synthesized superheavy nuclei using aforementioned techniques have short half-lives and hence are very sensitive toward decay. A descriptive analysis of various decay mechanisms is elaborated in the subsequent section.

1.3 Description of decay patterns

All known superheavy nuclei are unstable inspite of the existence of shell stabilization effects and decay via different modes known as ground and excited state decay mechanisms. This thesis work is confined to scrutinize the excited state decay modes which are further divided in two categories i.e. nCN and CN processes. Dynamical description of these decay modes follow different degrees of freedom. So, it becomes important to identify some bulk degrees of freedom like shape, charge, mass, energy, and angular momentum which can provide a realistic picture of collective behavior. In quantum mechanical fragmentation theory (QMFT) [42–46], proposed by Greiner and coworkers, following degrees of freedom are taken into consideration like (i) the distance R between nuclear centers, (ii) deformations ($\beta_{\lambda i}$), (iii) mass asymmetry (η), (iv) angle of rotation of nuclei in reaction plane (ϕ), (v) angle between colliding nuclei (θ), (vi) temperature, and (vii) angular momentum *etc.* Once the degree of freedom are chosen, then one of the key ingredient is to identify the appropriate nuclear potential. This multidimensional potential determine the trajectories which describe the probable reaction channels. After reaching the contact point by overcoming the Coulomb barrier, the intermediate system can follow different decay trajectories (also displayed in Fig. 1.3) which are explained in next sub-sections.

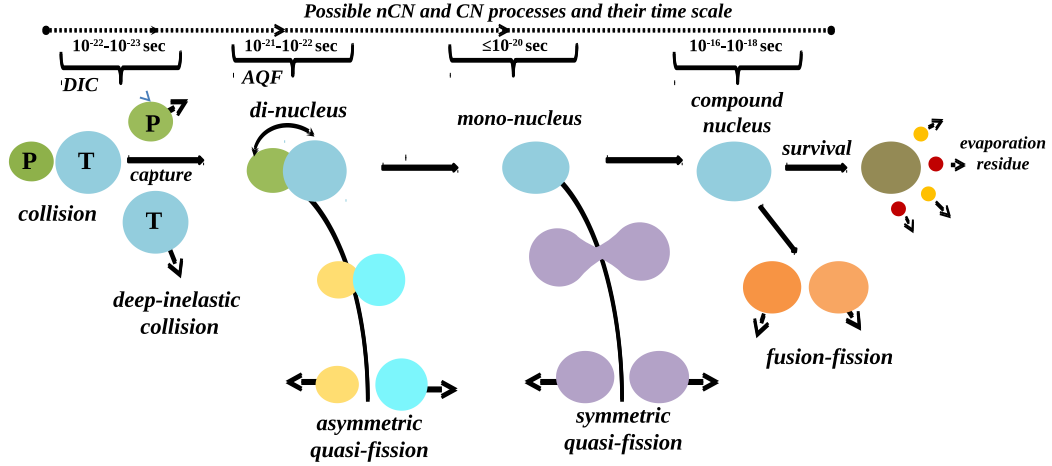


Figure 1.3: Decay scenario of superheavy elements via different compound and non-compound nucleus decay modes.

1.3.1 Non-compound nucleus processes

The non-compound nucleus (nCN) decay occurs at earlier stage of the collision, when the energetic projectile hit a stable target nucleus. In such kind of processes, the projectile interact with few nucleons of target nucleus and results into a non-equilibrated system [47]. One of the reaction type which occurs at above barrier energies, has the characteristic that the projectile loses only a moderate amount of energy with the exchange of a few nucleons. This reaction category is designated as ‘quasi-elastic’ reactions. For more violent collisions where the two nuclei overlap strongly with partial momentum transfer without trapping into potential well, the inelastic channel become more prominent and leads to deep-inelastic collision. The basic feature of these processes is that, one can observe scattered particles which (in contrast to the quasi-elastic reactions) loose major fraction of their kinetic energy but still have mass and charge close to those of the projectile [48, 49]. A comprehensive understanding of the deep-inelastic processes is not reported for superheavy nuclei as the dominating nCN process is quasi-fission (QF). QF is an intermediate process between deep-inelastic collisions and complete fusion, in which the composite/di-nuclear system runs through the potential well for small duration of time. After

that, di-nuclear system separates in two main excited fragments without forming a compound nucleus due to the action of repulsive Coulomb forces [50–55]. Some factors like mass-asymmetry, Coulomb factor Z_1Z_2 , deformations and orientations play a prime role in affecting the contribution of quasi-fission. Moreover, the microscopic features also play a vital role to understand the origin of quasi-fission processes.

The importance of shell effects in superheavy mass region can be realized via contribution of different decay modes observed across different magic lands. During the splitting of superheavy composite systems, the asymmetric fragments across ^{208}Pb having mass-asymmetry ~ 0.4 are termed as asymmetric quasi-fission (QF_{asym}). By the side of asymmetric component, the symmetric part may also be influenced by the existence of QF process. The observation of decay components across magic-Sn indicate the symmetric quasi-fission channel [33, 56]. QF is still a topic of profound experimental as well as theoretical exploration and hence, a real visualization of this process is still lacking.

1.3.2 Compound nucleus processes

When two nuclei overcome the Coulomb repulsive forces and reach the potential well after achieving equilibrium in all degree of freedoms, the intermediate fused system is called as compound nucleus and it decay generally via fusion-fission (or compound nucleus fission) mechanism and emission of light particles [57]. In superheavy mass region, fusion-fission occurs generally at near and above barrier energies when the equilibrated compound system has high E_{CN}^* and hence high fissility. The compound nucleus stabilizes by fission process and decays into two nearly equivalent fragments in the mass range $A = \frac{A_{CN}}{2} \pm 20$. On the other hand, the evaporation of light particles occurs from a CN which have smaller excitation energy after achieving equilibrium in all degree of freedoms. This compound system then de-excite through light particle evaporation (also termed as an evaporation residue (ER)). For superheavy nuclei, these light particles are generally neutrons and the observed ER cross-section is

very small as compare to the fusion-fission. As discussed earlier, among various parameters, the deformations and orientations are of great importance to study superheavy reaction dynamics because most of the colliding and decaying partners are deformed. Hence in the next section, an attempt is made to recognize the impact of deformations and orientations on the heavy ion induced reactions.

1.4 Role of deformations and orientations

The atomic nucleus, known as the quanta of many body system, is a reservoir of nucleons and various elementary particles. The interaction between proton-neutron and subsequent dynamics originates different nuclear properties such as radius, density, magnetic moment *etc* leading to different shapes of nuclear systems [58, 59]. Similar to inert gas atoms, nuclei with specific number of protons and neutrons (called magic numbers) are relatively more long-lasting and have spherical shapes. When adequate nucleons are appended far off these magic shell closures, the long range effective forces come into picture, which inturn deform the nuclear shape. This postulation of deformations was given by Pauli [60] whose experimental evidence was provided by Schüller and Schmidt [61]. The influence of deformations is feeble for the light mass nuclei, whereas majority of heavy or superheavy nuclei exhibit deformed configurations. The shape and the respective orientations of colliding nuclei is one of a foremost parameter which affects the endowment of aforementioned reaction mechanisms. The shape of two interacting nuclei either have spherically symmetric distribution or have deformed symmetry. The existence of deformations is contrived by related physical phenomena such as: (i) electric quadrupole moment (Q), (ii) rotational excitation spectra, and (iii) low energy single particle excitations. The distortion of shape is defined in terms of quadrupole moment (Q), which give birth to different degree of deformations. Quadrupole deformations (β_2) basically originate from quadrupole-quadrupole interactions having even parity (closed parity) and hence follow reflection symmetric principle. $\beta_2 > 0$ results in elongated

prolate configuration and $\beta_2 < 0$ represent the flattened oblate shape. In addition to β_2 -deformations, higher order distortions also exist, say for example octupole (β_3), hexadecupole (β_4), hexacontatetrapole (β_6) *etc.* Unlike β_2 -deformations, obtained from quadrupole moments, the β_3 -deformations are difficult to determine from direct measurements. The β_3 -deformations are originated from octupole-octupole interaction having parity doublet. These are pairs of nearly degenerate energy levels of the same spin but opposite parity. The configurational rearrangement between these levels breaks the symmetry and hence octupole deformations are reflection asymmetric [62]. The nucleus may also possess even higher order distortions like hexadecupole deformations (β_4). The presence of small static β_4 -deformations can have significant effect on the equilibrium shapes of deformed nuclei [63,64]. Inclusion of higher order deformations effects in addition to β_2 -deformations results in various compact configurations which are equally important in predicting the properties of some of the superheavy nuclei.

The idea of compactness was proposed by Oganessian *et al*, following which the theoretical study was performed by various authors [65–78]. Similar kind of attempt was made by Gupta *et al* and suggested optimum [69] and compact configurations [70, 71] of colliding nuclei depending on the magnitude and sign of deformations as shown in Fig. 1.4. The cold non-compact and hot compact configuration are obtained as optimum orientations corresponding respectively to lowest barrier/largest radius and highest barrier/smallest radius configurations. These orientations are suggested only on the basis of quadrupole deformations with small magnitude of hexadecupole distortions (β_4). With the inclusion of higher order deformations ($\beta_2, \beta_3, \beta_4$ *etc*), the optimum orientation criteria does not work and hence the compact orientations are worked out depending on magnitude and sign of deformed partners. It is worth introducing here that the deformed+deformed combinations form belly-to-belly structure whereas spherical+deformed combinations are termed as equatorial compact shapes as illustrated in Fig. 1.4. Extending this, the

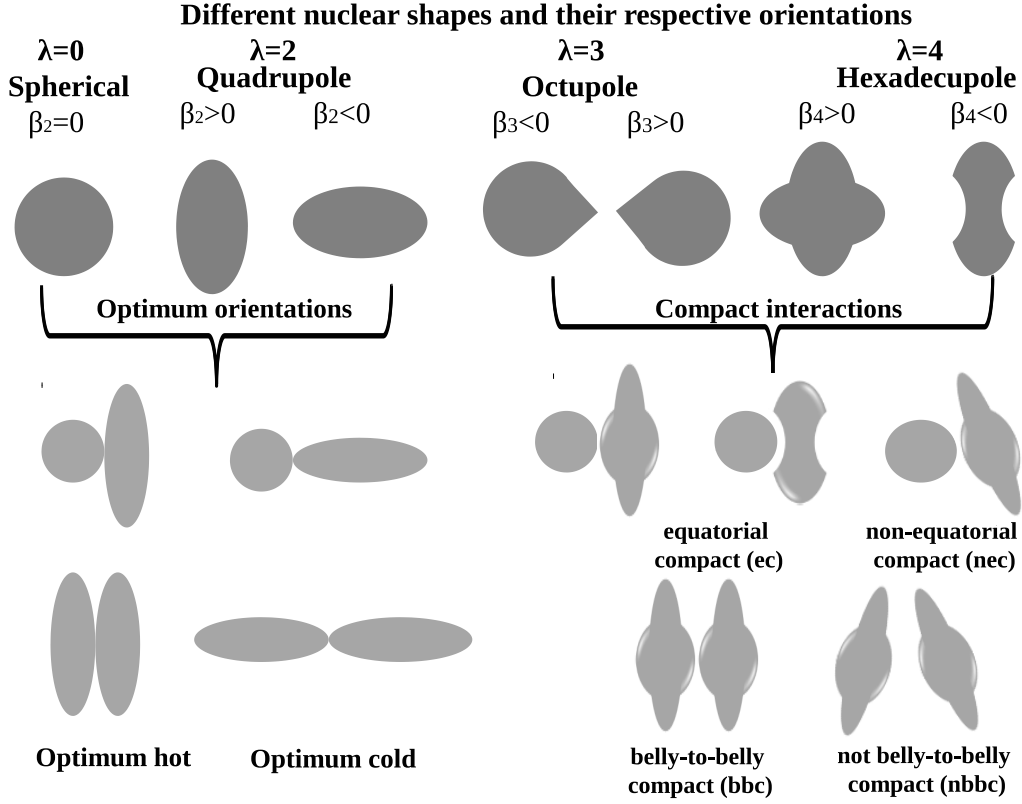


Figure 1.4: Representation of optimum and compact configuration of colliding nuclei based on the magnitude of deformations.

non-compact structures are also observed when large +ve β_4 is taken into account. Beside the static deformations, dynamic (temperature dependent) deformations can also be worked out and the corresponding impact on nuclear reaction dynamics can be explored.

1.5 Motivation behind the present work

From above literature review, it is manifested that the extensive efforts have been made to synthesize superheavy nuclei by employing variety of target-projectile combinations. Slowly periodic table is approaching the predicted magicity in superheavy regime and hence the dynamics of nuclear systems in this extreme mass region becomes more interesting and exciting than before. On the way toward the emer-

gence of evaporation residue, which keeps generating the option of providing new superheavy isotopes, fission processes are main obstacle. Hence, the comparative emergence of fission mechanisms need to be explored further for superior perceptive of the dynamics involved. Some important aspects related to the dynamics of superheavy nuclear systems will be analyzed in this thesis. The main focus of this work will be on:

- (i) The study of excited state decay modes such as fusion-fission, quasi-fission and nucleon evaporation in superheavy mass region.
- (ii) Fragmentation yield and Total kinetic energy (TKE) analysis of various fragments evolved in superheavy dynamics.
- (iii) Role of higher order deformations in the superheavy dynamics and analysis of associated compact orientations.
- (iv) To address the relevance of collective clusterization approach in view of available experimental data on superheavy dynamics.

1.6 Delineation of the Thesis

The logistics of this thesis is characterized as:

Chapter 2 outlines the theoretical descriptions of fusion and decay models used in the present work. This chapter starts with the detail of some basic parameters used in methodology and then elaborate the different constitutes of fragmentation potential. Succeeding section explains the Wong and ℓ -summed Wong models employed to figure out the fusion dynamics. Next, the numerical framework of dynamical cluster decay model (DCM) is discussed. The essential ingredient of DCM are preformation probability (P_0) and penetrability (P) whose relevant details are elaborated afterwards. The P_0 and P help in the determination of mass, yield, energy distribution, structural effects *etc.* With the help of aforementioned variables, the decay cross-sections are obtained whose expressions are mentioned in the end of this chapter. In the framework of aforementioned methodology, the work carried out to fulfill the

objective of this thesis is discussed in chapters 3 to 7.

First of all, **Chapter 3** explains the dynamics of neutron evaporation originated via hot and cold fusion reactions. Although, most of the thesis work is dedicated to the study the fission dynamics, so the neutron evaporation is studied to set a baseline for further calculations. As one of the reaction mechanism for the production of SHN is cold fusion, so starting with this, the propensity of $1n$ emission in Pb and Bi induced reactions are analyzed. For the purpose, DCM is employed to address the excitation functions of $1n$ evaporation (σ_{1n}). Relevance of deformation and orientation is probed on fragmentation potential and concluded that hot optimum orientations are more suitable within the DCM framework as the cold valleys were distinctly visible for the chosen reactions. To understand the dynamics better, a hierarchy is exercised which include the testing of higher order deformations (β_{4i}), energy enhancement, and the employment of sticking (I_S) and non-sticking (I_{NS}) moment of inertia approaches. Finally, the neutron evaporation of hot fusion reactions were studied.

As the fission processes hinder the formation of evaporation residues in super-heavy mass region, hence **Chapter 4** is dedicated to inspect the divergent aspect of fission dynamics. This chapter is intended to scrutinize the fission dynamics of ^{48}Ca and ^{238}U induced reactions. The fission and QF cross-sections of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei formed in ^{48}Ca -based reactions are addressed. The preformation probability (P_0) and penetrability (P) paths are analyzed to examine the behavior of decaying fragments. Additionally, the average total kinetic energy ($\overline{TKE}$) distributions of considered nuclei are analyzed. To generalize the result for complete superheavy mass region, the study is extended further for reactions formed via ^{238}U target. The experimental data of $Z=108, 112, 114$, and 120 superheavy nuclei is addressed and the work is further extended for $Z=104-120$ using the knowledge obtained from previous observations. The effect of deformations and respective

orientations on the relative endowment of fission and QF events is exercised. The physical significance for the origin of different peaks in fragmentation potential and preformation probability is explored.

In the previous chapter, the fission dynamics were explored by considering the static deformations only. In **Chapter 5**, the effect of dynamics (T-dependent) deformations is taken into account to study the fission path of superheavy nuclei. Additionally, in this chapter some predictions are made for least explored superheavy mass region. The dynamics of Z=105-111 superheavy nuclei is analyzed by employing different hot fusion reactions. The experimentally available data is addressed for $^{27}\text{Al} + ^{238}\text{U} \rightarrow ^{265}\text{Db}^*$ reaction to understand the fission processes. The role of dynamical (T-dependent) deformations is analyzed on the decay profile. With the inclusion of these deformations, a new fission valley appear in the fragmentation profile which is different from traditionally observed Pb valley. The Wong based calculations are performed to predict the fission cross-sections of $^{19}\text{F} + ^{248}\text{Cm} \rightarrow ^{267}\text{Db}^*$ and $^{18}\text{O} + ^{249}\text{Bk} \rightarrow ^{267}\text{Db}^*$ reactions. Beside this, an attempt is made to examine the least explored superheavy nuclei (*i.e.* Z=107-111) via hot fusion reactions. For the purpose, the available experimental data for these nuclei is addressed through ℓ -summed Wong model to set a systematic. After this, the fission cross-sections of Z=107-111 nuclei are predicted formed via different hot fusion reactions and the relevant role of quadrupole deformations (β_2) and orientations is explored in view of cross-sectional yield.

As the study of previous chapter shows that deformations and orientations influence the reaction dynamics significantly, hence this study is extended in **Chapter 6** by including the higher order deformations which was limited up to quadrupole (β_2) in the previous study. The role of higher order deformations with respect to their orientations is analyzed on the barrier characteristics (Barrier height (V_B) and Barrier radius (R_B)) of hot and cold fusion reactions. The exclusive role of reflection

SECTION 1.6: DELINEATION OF THE THESIS

symmetric quadrupole (β_2) and hexadecupole (β_4) deformations is examined in view of equatorial and non equatorial compact configurations. Beside this, the reflection asymmetric octupole (β_3) deformations are also included for better description of dynamics of superheavy nuclei.

Eventually, **Chapter 7** epitomize the results of present calculations discussed in the thesis as well as the future scope of extension of this work.

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Chapter 2

Methodology

2.1 Introduction

In the past few decades, immense endeavour have been comprehend to understand and analyse the physics of superheavy nuclei by employing diversing approaches on experimental as well as theoretical front. The first exploration of potential landscape was made with the phenomenological macro-microscopic shell corrections by Strutinsky [1]. Soon after, the non-relativistic self consistent Skyrme (or Gogny) Hartee-Fock [2, 3] and relative mean field theories [4] have been enforced. Complementing this, the collective potential energy surfaces by mass parameters enable the calculations of various heavy and superheavy nuclear dynamics. Elucidation along this line is sustained due to improved parametrization of macro-microscopic models. Some aspects of this kind are utilized in the present thesis to understand the advancement in the study of superheavy mass region. The foremost concern of this thesis work is to scrutinize the deformation and orientation effects, formation probability, penetrability, potential energy surfaces, shell-effects *etc* analogous with the formation and decay of superheavy compound nuclei produced via heavy-ion induced reactions. For the purpose, the Wong [5, 6] and ℓ -summed Wong [7] models are exercised to understand the fusion mechanism while the dynamical cluster decay model (DCM) [8–12] is exploited to confront the decay paths of nuclear composi-

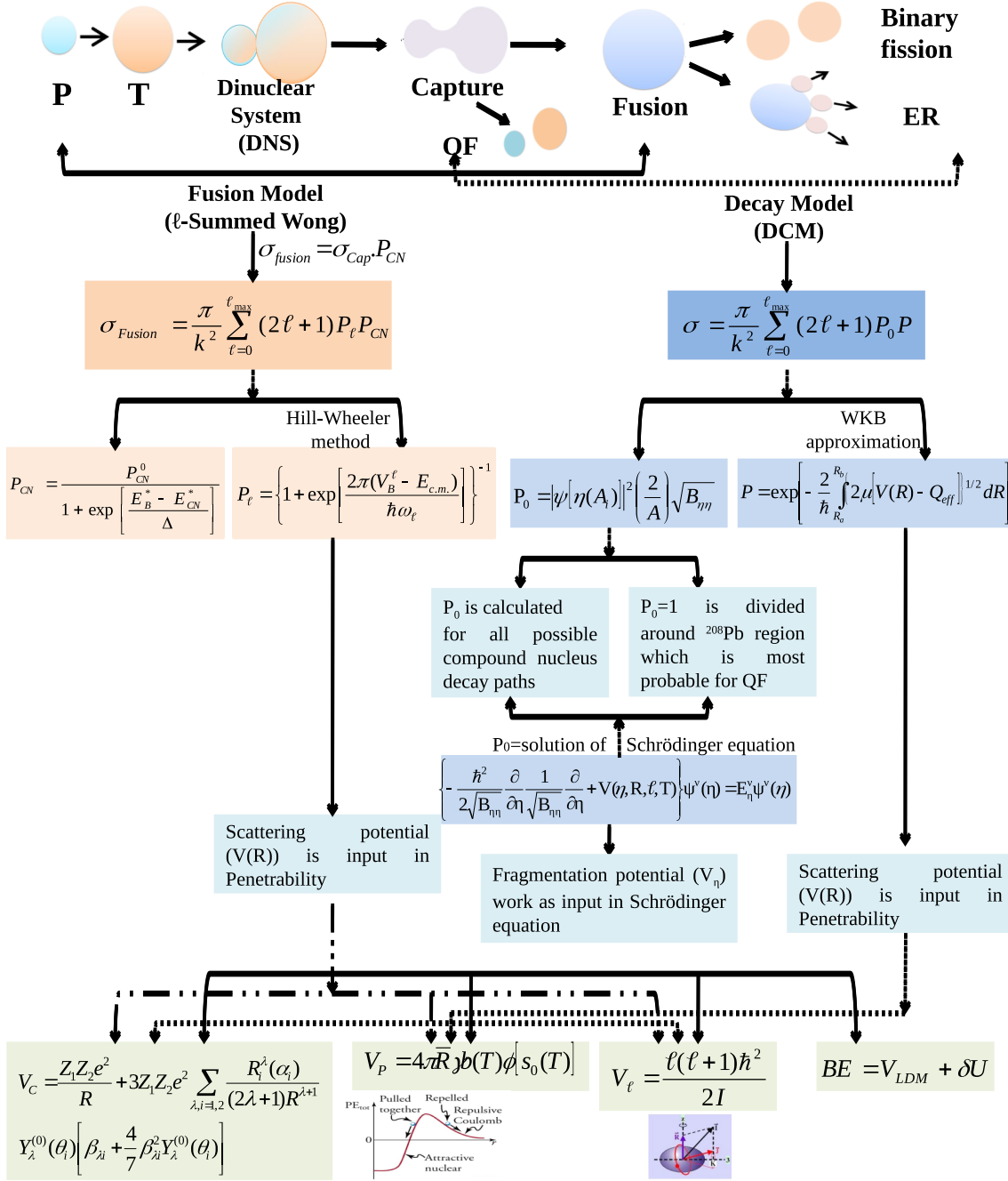


Figure 2.1: Flow chart representing the systematic of fusion and decay models for the study of SHN.

SECTION 2.2: DESCRIPTION OF SOME PRELIMINARY EXPRESSION USED IN METHODOLOGY

tion formed during heavy ion induced reactions. The overview of both models is demonstrated in Fig. 2.1 and the relevant mathematical structure is delineated in the upcoming sections of this chapter.

2.2 Description of some preliminary expression used in methodology

(i) **Energy relations:** The heavy ion-induced reactions incorporate the swapping of nucleons among the colliding nuclei. The energy of an incident beam is termed as (E_{beam} or E_{lab}) and when an energetic beam collides with the target in center-of-mass frame, it results in different kinetic energy of interacting channel called as $E_{c.m.}$. Most of the calculations are performed in the center-of-mass frame as it is straightforward in use and the energy conversion to other frames is easy. The entrance channel plays a pivotal aspect in the divination of center-of-mass energy ($E_{c.m.}$) and is related to beam energy (E_{beam}) as

$$E_{c.m.} = \frac{A_T}{A_T + A_P} E_{beam} \quad (2.1)$$

After collision, the target-projectile fuse and utilizes the $E_{c.m.}$ resulting in hot and rotating composite system. The extra energy of the composite system after fusion, which trigger the different decay mechanisms of unstable nucleus, is termed as excitation energy (E_{CN}^*). The $E_{c.m.}$ converted to E_{CN}^* can be estimated through relation

$$E_{CN}^* = E_{c.m.} + Q_{in} \quad (2.2)$$

with $Q_{in}=B_P+B_T-B_{CN}$ as the Q-value of reaction channel (B_P , B_T , and B_{CN}

are binding energies of reaction partners and compound nucleus). The E_{CN}^* of a hot and rotating compound nucleus provides the temperature which is obtained via [13]

$$E_{CN}^* = \frac{A_{CN}}{a} T^2 - T \quad (2.3)$$

The temperature evaluated from Eq. (2.3) provides the baseline for theoretical calculation proposed in this thesis.

(ii) Level density parameter (a): In Eq. (2.3), ‘ a ’ is the level density parameter; the key ingredient of reaction cross-section calculations. It gives the nucleon distribution in the nuclear levels which is usually obtained by analyzing the transitions between excited states. For sensitive prediction of theoretical outcomes, it is important to obtain level density parameter from reliable experimental data. The level density parameter is compound nucleus mass dependent, whose value varies from $a=7$ -11. In the present thesis work, $a=11$ is used which is suitable for the calculations in superheavy mass region.

(iii) Radius Vector (R): The radius parameter used for the calculations is deformation dependent. Any change in shape of nucleus results in change of surface properties and radius. The radius vector ($R_i(\alpha_i, T)$) of deformed and oriented nuclei is defined as

$$R_i(\alpha_i, T) = R_{0i}(T) \left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i) \right] (i = 1, 2) \quad (2.4)$$

with β as the deformation parameter has values $\lambda=2$ for quadrupole, $\lambda=3$ for octupole and $\lambda=4$ for hexadecupole. The deformations employed in this work are the static or temperature independent deformations ($\beta_{\lambda i}(0)$) of Möller *et al* [14]. The temperature dependance in deformation [15–17] (also termed as dynamic deformations in the present thesis work) is added through relation

SECTION 2.2: DESCRIPTION OF SOME PRELIMINARY EXPRESSION USED IN METHODOLOGY

$$\beta_{\lambda i}(T) = \exp\left(-\frac{T}{1.5}\right)\beta_{\lambda i}(0) \quad (2.5)$$

Here $i=1,2$ represent the first decaying fragment and its complementary fragment. α_i (measured clockwise) is the angle between symmetry axis and radius vector. In Eq. (2.4), R_{0i} is the radius parameter which has different values for different potentials [18–24]. Some of them are mentioned below

(i) The version of effective sharp radius given by Blocki [18] is as

$$R_{0i} = [1.28A_i^{1/3} + 0.8A_i^{-1/3} - 0.76]fm \quad (2.6)$$

(ii) For $Z \geq 38$, promorski *et al* [19] gives radius as

$$R_{0i} = 1.256A_i^{1/3} \left[1 - 0.202 \left(\frac{A_i - 2Z_i}{A_i}\right)\right] fm \quad (2.7)$$

(iii) The improved radius given by Reisdorf [20] is

$$R_{0i} = [1.28A_i^{1/3} + 0.8A_i^{-1/3} - 0.76] \left(1 - \frac{0.98}{[1.28A_i^{1/3} + 0.8A_i^{-1/3} - 0.76]^2}\right) fm \quad (2.8)$$

(iv) The radius obtained from liquid drop model with frozen densities [21] is

$$R_{0i} = [1.16A_i^{1/3} - 1.39A_i^{-1/3}]fm \quad (2.9)$$

(v) Christensen and Winther [22] gives different form of radius as

$$R_{0i} = [1.233A_i^{1/3} - 0.978A_i^{-1/3}]fm \quad (2.10)$$

(vi) Winther [23] further modified some parameters in radius and give

$$R_{0i} = [1.20A_i^{1/3} - 0.09] fm \quad (2.11)$$

The temperature dependence in above expression is included through expression

$$R_{0i}(T) = R_{0i}[1 + 0.0007T^2] \quad (2.12)$$

All the aforementioned input parameters are used further in the calculations of fragmentation potential, whose brief description is given below.

2.3 The Fragmentation Potential Energy (V)

The nuclear interactions are liable for binding of neutrons and protons in an atomic nucleus. Numerous models have been proposed to analyse the nucleonic distribution and to develop appropriate nuclear potentials. In the present thesis work, the collective potential, which serves as the starting point to study nuclear dynamics, is used. The proposed potential is calculated as a function of deformation ($\beta_{\lambda i}$) and orientation (θ_i) degree of freedom, relative separation R, mass and charge asymmetry co-ordinates, temperature *etc.* In terms of these parameters, the corresponding potential should comprehend as

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

The first term in above mentioned equation is the binding energy which is the sum of macroscopic liquid drop model energy (LDM) and microscopic shell-correction terms (δU). V_C , V_N , and V_ℓ are respectively Coulomb potential, proximity potential,

SECTION 2.3: THE FRAGMENTATION POTENTIAL ENERGY (V)

and centrifugal potential. The relevant description of these terms is given below.

2.3.1 Binding Energies (B_i)

The minimal energy needed to disassemble the nucleus into its components (i.e. neutron and protons) or the energy balance process in which nucleus splits into two fragments is termed as the nuclear binding energy. Numerous set of binding energies with different set of constants are available in literature. Every theory finds the origin of binding energies in term of Strutinsky prescription [1]. The fundamental intention is the use of liquid drop model to narrate the bulk part which is smoothly dependent on mass and charge numbers along with the phenomenological single particle model which describe the deviation of macroscopic part from smooth shell structure. According to this prescription, the binding energies are the sum of macroscopic (liquid drop model energy, V_{LDM}) and microscopic (“empirical” shell corrections, δU) part which can be read as

$$B_i(Z_i, A_i, T) = \sum_{i=1}^2 V_{LDM}(Z_i, A_i, T) + \delta U \exp\left(-\frac{T^2}{T_0^2}\right) \quad (2.14)$$

(i) Macroscopic part (V_{LDM}): The bulk properties of nuclei are determined by opting the semi-empirical mass formula of Seeger [25]. This formula provide a simple parametrization of binding energies of the nuclei, and is extended to non-zero excitation energies by Davidson [26] as

$$\begin{aligned} V_{LDM}(Z, A, T) = & \alpha(T)A + \beta(T)A^{\frac{2}{3}} + \left(\gamma(T) - \frac{\eta(T)}{A^{\frac{1}{3}}}\right) \left(\frac{(Z-N)^2 + 2|(Z-N)|}{A}\right) \\ & + \frac{Z^2}{R_0(T)A^{\frac{1}{3}}} \left(1 - \frac{0.7636}{Z^{\frac{2}{3}}} - \frac{2.29}{[R_0(T)A^{\frac{1}{3}}]^2}\right) + \delta(T) \frac{f(Z, A)}{A^{\frac{3}{4}}} \end{aligned} \quad (2.15)$$

The pairing function is $f(Z,A)=(-1,0,1)$ for even-even, even-odd, and odd-odd nuclei respectively. For ground state energies ($T=0$), the constants are obtained by extrapolation method for all even-even nuclei and 488 odd mass nuclei. The 488 odd nuclei were divided into two groups: (i) 282 nuclei are considered on beta stability line and on neutron poor side (ii) 206 nuclei on neutron rich side of beta stability line. The obtained constants are $\alpha(0)=-16.11$ MeV, $\beta(0)=20.21$ MeV, $\gamma(0)=20.65$ MeV, $\eta(0)=48.00$ MeV [25] and $\delta(0)=33.0$ MeV [27]. Later on, the bulk constant and proton-neutron asymmetry constant were refitted [28] to obtain the experimental binding energies of Audi Wapstra Table 1995 [29] and then for 2003 [30]. Wherever the same is not accessible, the theoretical estimates of Möller *et al* [14] were considered. The temperature dependence of β , γ , η , and δ coefficients in semi-empirical mass formula has been determined through least square fit to the canonical ensemble for nuclei throughout the periodic table by Davidson *et al* [26].

(ii) Microscopic part (δU): The empirical formula of shell corrections is taken from Myers and Swiatecki [31] and these are calculated as the difference between single particle contributions in the bunched and un-bunched states defined as

$$\delta U = 5.8 \left[\frac{F(Z) + F(N)}{(A/2)^{\frac{2}{3}}} - 0.26A^{\frac{1}{3}} \right] \quad (2.16)$$

with

$$F(X = N \text{ or } Z) = \frac{3}{5} \left(\frac{M_i^{\frac{5}{3}} - M_{i-1}^{\frac{5}{3}}}{M_i - M_{i-1}} \right) (X - M_{i-1}) + \frac{3}{5} \left(M_{i-1}^{\frac{5}{3}} - X^{\frac{5}{3}} \right) \quad (2.17)$$

Here M_i are the magic numbers for proton (2, 8, 20, 28, 50, 82, and 120 or 126) and neutron (2, 8, 20, 28, 50, 82, 126, and 184). The empirical shell corrections are exponential function of temperature (hence energy) as shown in Eq. (2.14) and diminishes with increase in temperature. It is relevant to mention that alternative

SECTION 2.3: THE FRAGMENTATION POTENTIAL ENERGY (V)

approaches like two-center shell model, Strutinsky method *etc* are also available in literature for the calculations of shell effects. In two-center shell model (TCSM) [32], shell corrections are derived from single particle potential with two-center level scheme and in its updated version i.e deformed two-center shell model (DTCSM) [33], the shape parameters are also included in calculations of microscopic effects. Strutinsky method based shell model calculations are derived from inhomogeneous distribution of nucleons as a function of deformations and their energy effects [1]. In this work, the deformations enter through radius term in the calculations, described in Eq. (2.4).

2.3.2 The Coulomb Potential (V_C)

According to liquid drop model, a nucleus is considered as a droplet on which electrostatic charge is considered to spread continuously throughout. Hence, two interacting nuclei possess the Coulomb forces which are repulsive in nature. This repulsive force is defined as

$$V_C(R) = \underbrace{V_C^{(0)}(R)}_{\text{Spherical part}} + \underbrace{V_C^{(cor)}(R)}_{\text{deformed part}} \quad (2.18)$$

In above equation, $V_C^{(0)}(R)$ is the spherical Coulomb potential obtained by considering the uniform charge distributions and is equal to $(Z_1 Z_2 e^2)/R$. For deformed charge distribution ($V_C^{(cor)}(R)$), the computational resolution of potential is very time consuming and therefore a good approximation method is required. In literature [5, 34–36], different authors suggest the following approximate expression for $V_C^{(Cor)}(R)$ as

$$V_C^{(cor)}(R) = Z_1 Z_2 e^2 \left[\frac{3\beta_{21} R_{01}^2}{5R^3} Y_{20}(\theta) + \frac{3\beta_{31} R_{01}^3}{7R^4} Y_{30}(\theta) + \dots \right] \quad (2.19)$$

The generalized form of Coulomb potential which include both terms should read as [34]

$$V_c(Z_i, \beta_{\lambda i}, \theta_i, \alpha_i, T) = \frac{Z_1 Z_2 e^2}{R(T)} + 3Z_1 Z_2 e^2 \sum_{\lambda, i=1,2} \frac{1}{2\lambda + 1} \frac{R_i^\lambda(\alpha_i, T)}{R(T)^{\lambda+1}} Y_\lambda^{(0)}(\theta_i) \left[\beta_{\lambda i} + \frac{4}{7} \beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i) \right] \quad (2.20)$$

$Y_\lambda^{(0)}(\theta_i)$ represents the spherical harmonics function for axially symmetric nuclei with radius parameter R_i as that of Eq. (2.4).

2.3.3 Rotational or Centrifugal Potential (V_ℓ)

In the rotation of a nucleus, shell-structure and symmetry term play a crucial role. The rotational degree of freedom originates due to breaking of rotational invariance, which introduces the deformations and related orientations of a nuclear system. The deviation from equilibrium frame results in the shape oscillation and rotational motion of a nucleus. In heavy-ion induced reactions, during mass relocation the angular momentum gets transferred into internal degree of freedom, and introduces frictional forces between two fragments which are in contact with each other. During this mass transfer, system pass through various stages. In the first stage (non-sticking) two nuclei slide on each other and exert a torque (rolling friction) on fragments which sets them into rotation until system reaches the rolling stage. After diminishing of rolling forces, fragments rotate in sticking configurations (see Fig. 2.2). The rotational energy calculated in terms of angular momentum (V_ℓ) and moment of inertia is expressed by relation

$$V_\ell(A_i, T, \beta_{\lambda i}, \theta_i, \alpha_i) = \frac{\ell(\ell + 1)\hbar^2}{2I(T)} \quad (2.21)$$

SECTION 2.3: THE FRAGMENTATION POTENTIAL ENERGY (V)

Transfer of angular momentum

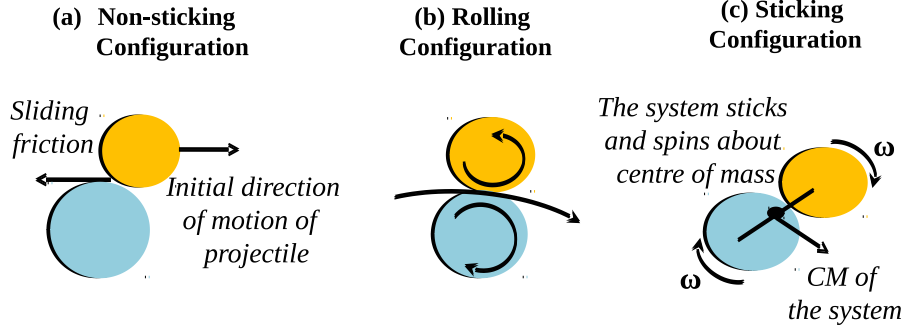


Figure 2.2: Schematic representation of (a) non-sticking, (b) rolling, and (c) sticking mode of moment-of-inertia (MOI) for two colliding nuclei.

In this equation, I is the moment of inertia (MOI) of rotating nucleus which can be calculated in various ways. In this thesis, the work is constrained to sticking and non-sticking configurations only whose expressions read as follow:

(i) Sticking moment of inertia (I_S): In this limit of moment of inertia, the nuclei with masses A_i and radii R_i rotate about their center-of-mass [37]. The resulting MOI is expressed as

$$I_S(T) = \mu R^2 + \frac{2}{5}m[A_1 R_1^2(\alpha_1, T) + A_2 R_2^2(\alpha_2, T)] \quad (2.22)$$

(ii) Non-sticking moment of inertia (I_{NS}): When the rotating nuclei are separated with $R > R_1 + R_2$, the non-sticking limits prevails [38] and related MOI become

$$I_{NS}(T) = \mu R^2 \quad (2.23)$$

with reduced mass, $\mu = \frac{A_1 A_2}{A_1 + A_2} m$ and m as nucleon mass. The experimentalists compute the angular momentum limits using I_{NS} . Due to the usage of Blocki's proximity potential (with $R \leq 2\text{fm}$), the sticking limits are more preferable in the collective clusterization criteria hence adopted in this thesis. The preceding applications [11] advocate the preference of I_S approach for the study of evaporation as well as the fission dynamics. Moreover, I_{NS} limits seem relevant only for the

evaporation residue study.

2.3.4 The Nuclear Proximity Potential (V_N)

The identification of appropriate nuclear potential is very essential in the fusion and decay dynamics of nuclei. The precise diagnosis of nuclear potential between two nuclei is a strenuous assignment. Multitudinous attempts have been carried out to derive a simple and accurate form of such potentials and proximity potential being one option suggested by Deryagin [39]. This potential originates due to the close proximity (comparable to $\approx 2\text{fm}$) of two nuclei in fusion or decay state when the surface region is thin compared to the size of the nucleus. Blocki has modified and generalized the theorem given by Deryagin to explain proximity potential for spherical nuclei [18], according to which the force between two curved surfaces is proportional to geometric factors depending on the mean curvature radius of interacting surfaces and universal function (depends on separation distance). The expression can be approximated by the form

$$V_N(s_0) = \underbrace{4\pi\bar{R}\gamma b}_{\text{geometry}} \underbrace{\Phi(s_0)}_{\text{surface parameter}} \quad (2.24)$$

The dependance on nuclear surface separation is completely determined by universal function $\Phi(s_0)$ [18]. The shape and structural properties of nuclei are described by geometric factor which include $\bar{R}$; the mean curvature radius, γ ; the specific nuclear surface tension and b ; the diffuseness. This expression was further extended by R. K. Gupta *et al* [40] for deformed and oriented nuclei. The modified expression should read as

$$V_N(A_i, R, T, \beta_{\lambda i}, \theta_i) = 4\pi\bar{R}(T)\gamma b(T)\Phi(s_0(T)) \quad (2.25)$$

The radius of curvature ($\bar{R}$) in the principal planes of each of two nuclei, which are

SECTION 2.3: THE FRAGMENTATION POTENTIAL ENERGY (V)

axially symmetric ($\phi=0$), at the point of closest approach is given by [41]

$$\frac{1}{\bar{R}^2} = \frac{1}{R_{11}R_{22}} + \frac{1}{R_{21}R_{12}} \quad (2.26)$$

with

$$R_{i1}(\alpha_i) = \frac{[R_i^2(\alpha_i) + R_i'^2(\alpha_i)]^{\frac{3}{2}}}{R_i^2(\alpha_i) + 2R_i'^2(\alpha_i) - R_i(\alpha_i)R_i''(\alpha_i)} \quad (2.27)$$

$$R_{i2}(\alpha_i) = \frac{R_i(\alpha_i) \sin \alpha_i}{\cos(\pi/2 - \alpha_i - \delta_i)} \quad (2.28)$$

with $R_i'(\alpha_i)$ and $R_i''(\alpha_i)$ as the first and second order derivative of $R_i(\alpha_i)$. The case of colliding nuclei lying in same plane with nuclear separation distance R having orientation θ_i is shown in Ref. [40]. The universal function ($\phi(s_0)$) in Eq. (2.25), independent of shape and geometry, depends on minimum separation distance s_0 . For fixed R , the minimum separation distance s_0 is defined as

$$s_0 = R - X_1 - X_2 = R - R_1(\alpha_1)\cos(\theta_1 - \alpha_1) - R_2(\alpha_2)\cos(180 + \theta_2 - \alpha_2) \quad (2.29)$$

with the minimization conditions

$$\begin{aligned} \tan(\theta_1 - \alpha_1) &= -\frac{R_1'(\alpha_1)}{R_1(\alpha_1)} \\ \tan(180 + \theta_2 - \alpha_2) &= -\frac{R_2'(\alpha_2)}{R_2(\alpha_2)}. \end{aligned} \quad (2.30)$$

which results in

$$\begin{aligned}\delta_1 &= \theta_1 - \alpha_1 \\ \delta_2 &= 180 + \theta_2 - \alpha_2.\end{aligned}\tag{2.31}$$

The diffuseness of the nuclear surface reads as [42]

$$b(T) = \left[\pi/2\sqrt{3} \ln 9 \right]_{t_{10-90}} (1 + 0.009T^2) = 0.99(1 + 0.009T^2) \tag{2.32}$$

In the application of above formula to nuclear problems, variety of these potentials take care of different aspects including the isospin dependance for example, Prox-77, Prox-00, Prox-88, Bass-73, CW-86, BW-91, AW-95 *etc.* I have used Prox-77, Prox-00, and Prox-88 in this thesis, the detail of which can be seen in Ref. [18, 43, 44]. A brief description of these potentials is given below:

(i) Proximity 1977 (Prox-77): As per the initial version of proximity potential 1977 [18], the inter-connecting potential between two surfaces can be written as

$$V_N(A_i, R, T, \beta_{\lambda_i}, \theta_i) = 4\pi \bar{R}(T) \gamma b(T) \Phi\left(\frac{r - C_1 - C_2}{b}\right) \tag{2.33}$$

The universal function $\Phi(s_0 = \frac{r - C_1 - C_2}{b})$ for this potential is parameterized as

$$\Phi(s_0) = \begin{cases} -\frac{1}{2}(s_0 - 2.54)^2 - 0.0852(s_0 - 2.54)^3; & s_0 \leq 1.2511 \\ -3.437 \exp(-\frac{s_0}{0.75}); & s_0 \geq 1.2511 \end{cases} \tag{2.34}$$

The surface energy coefficient (γ) which depends on the neutron and proton excess is

$$\gamma = (\gamma_0 = 0.9517) \left[1 - (k_s = 1.7826) \left(\frac{N - Z}{A} \right)^2 \right] \text{MeV fm}^{-2} \tag{2.35}$$

where N and Z are the total number of neutrons and protons. The surface width b has been evaluated close to unity.

(ii) Proximity 1988 (Prox-88): The nuclear surface tension mentioned in Eq. (2.35) was further modified by Möller and Nix [43] which give stronger attraction compared to Prox-77. The values of coefficients modified as $\gamma_0=1.2496$ Mev/fm² and $k_s=2.3$ respectively. Reisdorf [20] labelled this version of potential as “Proximity 1988”.

(iii) Proximity 2000 (Prox-00): To remove the discrepancy between Prox-77 and experimental data, Myers and Swiatecki modified the nuclear potential using up-to-date radii and surface tension coefficients estimated using droplet model [44]. The details of this potential can be seen in Ref. [24].

The collective sum of binding energies, Coulomb potential, proximity potential, and rotational energy gives the fragmentation potential ($V=B.E.+V_C+V_N+V_\ell$) whereas sum of Coulomb, proximity, and rotational potential define the scattering potential ($V=V_C+V_N+V_\ell$). Using these potentials as input, the fusion and decay dynamics is explored, as explained in subsequent sections.

2.4 Fusion Model based on Wong approach

2.4.1 Capture or total cross-section:

Wong derived the capture cross-section [5,6] in term of angular momentum partial wave which reads as

$$\sigma_{cap}(E_{c.m.}, \theta_i) = \sum_{\ell} \sigma_{\ell} = \frac{\pi \hbar^2}{2\mu E_{c.m.}} \sum_{\ell=0}^{\infty} (2\ell + 1) P_{\ell}(E_{c.m.}, \theta_i) \quad (2.36)$$

Here μ is the reduced mass and P_{ℓ} is the transmission coefficient or the tunnelling probability. The formula for the calculation of tunnelling probability given by Hill-

Wheeler [45] reads as

$$P_\ell(E_{c.m.}, \theta_i) = \left[1 + \exp \left(\frac{2\pi(V_B^\ell(E_{c.m.}, \theta_i) - E_{c.m.})}{\hbar\omega_\ell(E_{c.m.}, \theta_i)} \right) \right]^{-1} \quad (2.37)$$

In above equation, the barrier curvature $\hbar\omega_\ell$ is evaluated at barrier position $R=R_B^\ell$ with respect to which maximum barrier height V_B^ℓ is obtained. R_B^ℓ is calculated from the condition $|dV_T^\ell(R)/dR|_{R=R_B^\ell} = 0$. The barrier curvature is evaluated using the following relation

$$\hbar\omega_\ell(E_{c.m.}, \theta_i) = \hbar \left[d^2V_T^\ell(R)/dR^2|_{R=R_B^\ell}/\mu \right]^{1/2} \quad (2.38)$$

Wong further simplified Eq. (2.37) under specific conditions of barrier height, barrier radius and curvature as: (i) $\hbar\omega_\ell \approx \hbar\omega_0$ and (ii) $V_B^\ell \approx V_B^0 + \frac{\hbar^2\ell(\ell+1)}{2\mu R_B^0{}^2}$, assuming $R_B^\ell \approx R_B^0$.

As the contribution of partial waves is enormous towards cross-section, the cross-sections can be obtained by integrating over ℓ -values. With this assumption, the Wong formula for capture cross-section read as

$$\sigma_{Cap}(E_{c.m.}, \theta_i) = \frac{R_B^0{}^2 \hbar\omega_0}{2E_{c.m.}} \ln \{ 1 + \exp \left[\frac{2\pi}{\hbar\omega_0} (E_{c.m.} - V_B^0) \right] \} \quad (2.39)$$

In above equation, $\sigma_{Cap}(E_{c.m.}, \theta_i)$ is calculated for each orientation and is then integrated over angle θ_i (i=1,2) to get final cross-sections as

$$\sigma_{Cap}(E_{c.m.}, \theta_i) = \int_{\theta_i=0}^{\pi/2} \sigma(E_{c.m.}, \theta_i) \sin \theta_1 d\theta_1 \sin \theta_2 d\theta_2 \quad (2.40)$$

This Wong formula is satisfactory to address the capture cross-section at energies near the barrier and the cross-sections are overestimated at higher energies. So, this formula was modified by Gupta and collaborator [7] by including ℓ -summation upto

SECTION 2.4: FUSION MODEL BASED ON WONG APPROACH

ℓ_{max} rather than ∞ . This modified formula is known as ℓ -summed Wong formula, where the maximum possible angular momentum (ℓ_{max}) of a system at a given energy is calculated using relation [46]

$$\ell_{max} = \frac{R_a \sqrt{2\mu[E_{c.m.} - V(R_a, \ell = 0)]}}{\hbar} \quad (2.41)$$

2.4.2 Fusion cross-section:

The fusion for superheavy nuclei constitute only a part to the capture events, so the fusion cross-section is always equal to or less than the capture cross-section and is expressed as

$$\sigma_{fusion}(E_{c.m.}, \theta_i) = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell + 1) P_{\ell} P_{CN} \quad (2.42)$$

Compound nucleus formation probability (P_{CN}): In above equation, P_{CN} is the compound nucleus formation probability. The mean fissility parameter (x_m) dependent formation probability (P_{CN}) is defined as the linear combination of the effective fissility parameter x_{eff} and compound nucleus fissility parameter x_{CN} . The mean fissility parameter [47] is defined as

$$x_m = 0.75x_{eff} + 0.25x_{CN} \quad (2.43)$$

The compound nucleus fissility parameter x_{CN} [48] is the ratio of competing Coulomb and nuclear forces for compact shapes and is given by

$$x_{CN} = \frac{(Z^2/A)}{(Z^2/A)_{crit}} = \frac{(Z^2/A)}{50.883[1 - 1.7826I^2]} \quad (2.44)$$

where $I=(A-2Z)/A$ is the relative neutron excess of compound nucleus. The effective fissility parameter x_{eff} [48] which includes the effect of mass and charge asymmetry is as

$$x_{eff} = \frac{4Z_1Z_2/[A_1^{1/3}A_2^{1/3}(A_1^{1/3} + A_2^{1/3})]}{50.883[1 - 1.7826I^2]} \quad (2.45)$$

The value of P_{CN}^0 , which is the “asymptotic” fusion probability, was proposed by Zagrebaev and Greiner [49]. It depends on the above parameters of the colliding nuclei by the relation

$$P_{CN}^0 = \frac{1}{1 + \exp(x_m - \xi)/\tau} \quad (2.46)$$

The parameters of Eq. (2.46) giving better agreement with the estimated values of P_{CN}^0 for reactions with actinide targets are defined as $\tau=0.0226$ and $\xi= 0.721$ [47]. The energy dependence of fusion probability can be approximated by simple relation as [49]

$$P_{CN}(E^*, \ell) = \frac{P_{CN}^0}{1 + \exp[(E_B^* - E_{CN}^*)/\Delta]} \quad (2.47)$$

Here E_B^* is the excitation energy of compound nucleus equal to bass barrier, E_{CN}^* is the excitation energy, and Δ is the adjustable parameter of about 4 MeV. Also, the Businaro-Gallone mass asymmetry (α_{BG}) is calculated using empirical relation [50]

$$\alpha_{BG} = \begin{cases} 0; & x_{CN} < 0.396 \\ 1.12\sqrt{\frac{x_{CN}-0.396}{x_{CN}-0.156}}; & x_{CN} > 0.396 \end{cases} \quad (2.48)$$

2.5 Decay dynamics using collective clusterization approach

The collective clusterization based DCM [8–12] has been used to scrutinize the nuclear decay scenario in light, medium, heavy, and superheavy mass region of periodic table. DCM adopted Quantum Mechanical Fragmentation Theory (QMFT) [51–55] which finds its basis in “two center shell model” (that is widely used model whose

SECTION 2.5: DECAY DYNAMICS USING COLLECTIVE CLUSTERIZATION APPROACH

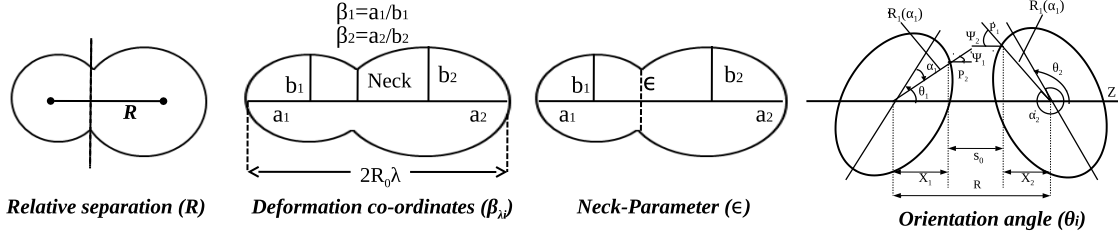


Figure 2.3: Explanation of nuclear shapes and associated parameters used in QMFT.

potential is enumerated using Strutinsky method). The shapes and parameters considered in the QMFT theory are illustrated in Fig. 2.3. The ellipsoidal shapes with individual deformations and overall size of a system explain the mass division of a system along with parameters such as: (i) The center separation R equivalent to $2R_0\lambda$, (ii) neck controlling parameter $\varepsilon=E_0/E'$ with E_0 and E' as actual and fixed barrier heights, (iii) deformation co-ordinates ($\beta_{\lambda i}$) and related orientations (θ_i) where $\lambda_i=2,3,4\dots$ and $i=1,2$, and (iv) asymmetry co-ordinates (mass (η_A) and charge(η_Z)), depending on fragment mass as

$$\eta_A = \frac{A_1 - A_2}{A_1 + A_2}; \quad \eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad (2.49)$$

with η domain as $0 \leq |\eta| \leq 1$ which allow processes ranging from complete fusion with $|\eta|=1$ to symmetric ($|\eta|=0$) decay.

Using the aforementioned collective co-ordinates, Hamiltonian ($H=K+V$) is calculated. Further, the related potential (V) is minimized in η_Z co-ordinate and Schrödinger wave equation is separated in mass parameter η and relative or center separation R with Hamiltonian as

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

$$H = - \underbrace{\left[\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial\eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial\eta} + \frac{\hbar^2}{2\sqrt{B_{RR}}} \frac{\partial}{\partial R} \frac{1}{\sqrt{B_{RR}}} \frac{\partial}{\partial R} \right]}_{\text{Kinetic energy part}} + \underbrace{V(\eta) + V(R)}_{\text{potential energy part}} \quad (2.50)$$

In above equation, $B_{\eta\eta}$ are the hydrodynamical mass parameters given in classical model of Kröger and Scheid whose details can be found in Ref. [56]. Instead of these, one can also use microscopic cranking masses [57, 58]. The kinetic and potential energy taken into account are decoupled in term of η and R . The coupling term ($\propto \frac{\partial^2}{\partial\eta\partial R}$), resulting in small coupled masses ($B_R\eta \ll (B_{RR}B_{\eta\eta})^{1/2} / B_R\eta_z \ll (B_{RR}B_{\eta_z\eta_z})^{1/2}$) is overlooked. Hence, the Schrödinger equation separated in decoupled η and R co-ordinate takes the form as

$$\left[-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial\eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial\eta} + V(\eta, T) \right] \psi^\nu(\eta) = E_\eta^\nu \psi^\nu(\eta) \quad (2.51)$$

and

$$\left[-\frac{\hbar^2}{2\sqrt{B_{RR}}} \frac{\partial}{\partial R} \frac{1}{\sqrt{B_{RR}}} \frac{\partial}{\partial R} + V(R, T) \right] \psi^\nu(R) = E_R^\nu \psi^\nu(R) \quad (2.52)$$

The generalized solution of above equations is of the form $|\psi^\nu(\eta)|^2$ and $|\psi^\nu(R)|^2$ respectively. The solution of Eq. (2.51) (*i.e.* $|\psi^\nu(\eta)|^2$) gives the preformation probability (P_0) and that of Eq. (2.52) (*i.e.* $|\psi^\nu(R)|^2$) provide penetrability or tunneling probability (P). As in this model we assume that R is slowly varying function so instead of solving the Schrödinger equation in R co-ordinates, the penetrability (P) is calculated through Wentzel Kramers Brillouin (WKB) approximation [59]. $V(\eta, T)$ is the collective fragmentation potential described earlier in Sec. 2.3.

SECTION 2.5: DECAY DYNAMICS USING COLLECTIVE CLUSTERIZATION APPROACH

2.5.1 Preformation Probability (P_0)

Preformation probability (P_0), solution of Eq.(2.51) in terms of η -coordinates, give the probability of formation of decaying fragments at the composite stage. The same is obtained for each channel (*i.e.* at all η) using the input of fragmentation potential at fixed $R=R_a$ as

$$P_0(A_2) = |\psi_R^\nu(A_2)|^2 \frac{2}{A} \sqrt{B_{\eta\eta}(A_2)} \quad (2.53)$$

with vibrational states as $\nu=0,1,2,3...$ referring ground ($\nu=0$) and excited ($\nu>0$) state solutions. The value of wave function $|\psi^\nu|$ at different vibrational states is calculated assuming Boltzmann function for excited states as

$$|\psi(\eta)|^2 = \sum_{\nu=0}^{\infty} |\psi^\nu(\eta)|^2 \exp\left(-\frac{E_\eta^\nu}{T}\right) \quad (2.54)$$

It is worth mentioning here that the mass or charge transfer co-ordinates (*i.e.* asymmetries) are directly measurable quantities and hence DCM calculated preformation probability (P_0) give adequate idea of mass distribution in decay channels. For nCN processes such as quasi-fission QF, P_0 is considered unity and is distributed equally among most probable fragments around QF peak. In superheavy mass region, such peaks are observed around different isotopes of Lead (Pb) and their complementary fragments.

2.5.2 Penetrability or Tunneling Probability (P)

Penetrability (P) is the probability of preformed fragments to overcome the barrier for decay. It is obtained by applying WKB integral [59] which is expressed as

$$P = \exp \left[-\frac{2}{\hbar} \int_{R_a}^{R_b} \{2\mu[V(R) - Q_{eff}]\}^{1/2} dR \right] \quad (2.55)$$

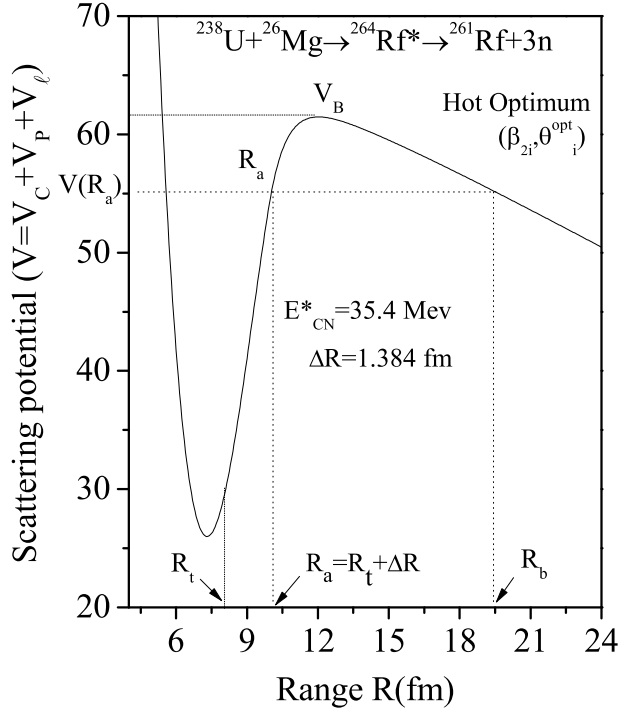


Figure 2.4: The scattering potential $V(R)$ at $\ell=\ell_{max}$ for the decay of $^{264}\text{Rf}^*$ super-heavy nucleus with all the important parameter marked.

The aforesaid integral is solved analytically by parameterizing scattering potential $V(R)$ as

$$V(R) = \begin{cases} a_1 R + a_2 R^2; R_0 \leq R \leq R_t \\ V(R_t) + m(R - R_t); R_t \leq R \leq R_m \\ V_B - \frac{1}{2}k(R - R_B)^2; R_m \leq R \leq R_h \\ V(R_h) - c_1 \frac{R - R_h}{R}; R_h \leq R \leq R_i \\ V(R_i) - c_2 \frac{R - R_i}{R}; R_i \leq R \leq R_b \end{cases} \quad (2.56)$$

The constants a_i ($i=1,2$) are determined with $V(R)=Q$ for $R=R_0$ and $V(R)=V(R_t)$ at $R=R_t$ boundary conditions. This is the undetermined part of potential and is avoided in the calculations. Hence, transmission probability consist of potential for $R>R_t$ as given in Eq. (2.56). The integral of penetrability (see Eq. (2.55)) is solved using reduced mass (μ) instead of hydrodynamical masses (B_{RR}) as

SECTION 2.5: DECAY DYNAMICS USING COLLECTIVE CLUSTERIZATION APPROACH

$B_{RR} \approx \mu$ based on incompressible irrotational flow. R_a and R_b are respectively the first and second turning point on penetration path. The first turning point (R_a) is obtained by relation

$$\begin{aligned} R_a &= R_1(\alpha_1, T) + R_2(\alpha_2, T) + \Delta R(\eta, T) \\ &= R_t(\alpha_i, T) + \Delta R(\eta, T) \end{aligned} \quad (2.57)$$

The radius parameter (R_i) used in above equation are defined earlier in Sec. 2.2 of this chapter. These turning point are kind of injection points (saddle and scission) used in statistical models [60, 61] and location is determined by some adjustable parameter. A similar method is used in DCM in term of neck-length parameter (ΔR). ΔR describes the relative separation between two fragments, worked out almost in same way as done in two center shell model [51].

In Eq.(2.55), $V(R)$ and Q_{eff} are respectively scattering potential ($=V_C+V_N+V_\ell$) and effective Q-value which are further equal to total kinetic energy (TKE) of the decay process and written as $V(R_a, T) = V(R_b, T) = TKE(T) = Q_{eff}$ with $V(R_a)$ and $V(R_b)$ as scattering potentials experienced by the fragment at turning point of barrier. The average TKE ($\overline{TKE}$) can be estimated as

$$\overline{TKE}(A_2) = \sum_{\ell=0}^{\ell_{max}} \frac{\sigma_\ell(A_2)}{\sigma(A_2)} TKE(\ell, A_2) \quad (2.58)$$

2.5.3 Decay Cross-sections

The decay cross-sections are calculated within “partial wave analysis” method. In superheavy mass region, total or capture cross-section (σ_{total} or σ_{Cap}) is the sum of quasi-fission (σ_{QF}), compound nucleus fission (σ_{CNF}), and evaporation residue (σ_{ER}) cross-sections (i.e. $\sigma_{Cap} = \sigma_{QF} + \sigma_{CNF} + \sigma_{ER}$). In term of partial waves, the fragments’s formation or decay cross-sections can be written as

$$\sigma = \sum_{\ell=0}^{\ell_{max}} \sigma_{\ell} = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell + 1) P_0 P; \quad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (2.59)$$

ℓ_{max} is the maximum angular momentum values contributing to the cross-section, calculated at a point where $\sigma_{ER}(\ell) \rightarrow 0$ and μ as the reduced mass. Preformation probability (P_0) and Penetrability (P) are described earlier in Sec. 2.5.1 and 2.5.2 respectively.

Based on the above layout of theoretical methodology, the the formation and decay analysis of various reactions peculiarities of superheavy mass region is worked out. The related results are discussed in chapter 3 to 7.

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Chapter 3

Analysis of neutron evaporation in superheavy mass region

3.1 Introduction

The extension of periodic table beyond the actinide series is mainly undertaken by the heavy ion reactions. Following this, two major approaches have been employed to address the heavy/superheavy mass region, known as cold fusion and hot fusion synthesis. Cold interaction avails closed shell Pb and Bi based targets [1,2], whereas deformed targets with ^{48}Ca projectile are used in the hot fusion reactions [3,4]. Both fusion mechanisms have several features in common while differ in many aspects, such as excitation energy, entrance channel asymmetry, survival probability *etc.* Lower excitation energies in $E^*_{CN}=10\text{-}30$ MeV range are required to address the superheavy reaction dynamics through the cold interactions. This leads to the higher endurance of CN because the transition to the ground state take place with the emission of one/two neutron(s). These reactions were proposed in mid 1970's for the formation of new trans-actinide nuclei. In succeeding years, the elements Bh (107), Hs (108), Mt (109), Ds (110), Rg (111), and Cn (112) were discovered using the same interaction approach [5–7]. The last synthesized nucleus was $Z = 113$ with maximum production cross-section of 55 pb [8]. The properties of these SHEs formed

Table 3.1: Catalogue of cold fusion reactions probed in experiments at different laboratories. The reactions are organised as per Z of compound nucleus and Coulomb parameter $z=Z_1Z_2/(A_1^{1/3}+A_2^{1/3})$. In addition to this, the Coulomb barrier and maximum value of center-of-mass energy ($E_{c.m.}$) are also reported.

Z	Reaction	Coulomb barrier (MeV)	Coulomb Parameter (MeV)	$E_{c.m.}$ (MeV)	References
104	$^{208}\text{Pb}+^{50}\text{Ti}\rightarrow^{258}\text{Rf}^*$	192.56	187.76	194.02	[16]
105	$^{209}\text{Bi}+^{50}\text{Ti}\rightarrow^{259}\text{Db}^*$	195.14	189.84	193.79	[17]
106	$^{208}\text{Pb}+^{52}\text{Cr}\rightarrow^{260}\text{Sg}^*$	209.96	203.78	207.20	[18]
107	$^{209}\text{Bi}+^{54}\text{Cr}\rightarrow^{263}\text{Bh}^*$	214.04	205.06	218.72	[19]
108	$^{208}\text{Pb}+^{58}\text{Fe}\rightarrow^{266}\text{Hs}^*$	227.89	217.64	224.99	[20]
109	$^{209}\text{Bi}+^{58}\text{Fe}\rightarrow^{267}\text{Mt}^*$	230.95	220.08	225.41	[20]
110	$^{208}\text{Pb}+^{64}\text{Ni}\rightarrow^{272}\text{Ds}^*$	242.40	231.34	243.68	[21]
111	$^{209}\text{Bi}+^{64}\text{Ni}\rightarrow^{273}\text{Rg}^*$	246.19	233.93	247.40	[22]
112	$^{208}\text{Pb}+^{70}\text{Zn}\rightarrow^{278}\text{Cn}^*$	255.70	244.87	260.13	[23]
113	$^{209}\text{Bi}+^{70}\text{Zn}\rightarrow^{279}\text{Nh}^*$	259.10	247.62	259.87	[8]

in cold fusion reactions were investigated theoretically by various authors [9, 10].

Inspite of the higher formation probability associated with the cold fusion approach as compared to the hot interaction process, a reasonable decrement in the cross-sections of nuclei with increasing Z was reported. The decay cross-sections are suppressed approximately six to seven times as one goes from $Z=104$ to $Z=113$ superheavy nucleus. This may be due to the increase in the Coulomb parameter $z=Z_1Z_2/(A_1^{1/3}+A_2^{1/3})$ (values are reported in Table 3.1), which plays eminent part in the formation and decay of the heavy/superheavy nuclei. The hot and cold fusion processes are generally hindered through the high Coulomb repulsions, hence characterized by competing processes like QF, quasi-elastic and deep inelastic events along with FF and neutron evaporation. It is important to mention that the addressal of these decay channels in the framework of DCM [11–15] is exercised mainly for the “hot fusion” reactions. The structure of the potential energy surfaces (PES)

reveals the importance of deformations and optimum orientations of nuclei formed via hot fusion interactions [12, 13]. In addition to this, the significance of above and below barrier energies [13], angular momentum and magic shell closures [14] is also explored using this methodology in the recent past. In view of these parameters, the present analysis is executed to understand the dynamics of the cold fusion reactions [8, 16–23], characterized by spherical targets and ^{50}Ti to ^{70}Zn projectile beams. The details of the chosen reactions are given in Table 3.1, where the magnitudes of the Coulomb barrier, Coulomb parameter, and $E_{c.m.}$ etc are reported. Note that the maximum values of $E_{c.m.}$ are measured around the Coulomb barrier. In order to address the above table, $1n$ cross-sections of $Z_{CN}=104-113$ nuclei are computed using the spherical and deformed fragmentation approaches in the framework of DCM [11–15]. The deformation effects are included upto β_{2i} , with “optimum” orientations (θ_i^{opt}) of nuclei or fragments. The optimum orientations are selected on the basis of scattering potentials or equivalently the barrier profile of fusing nuclei which govern through the signs (prolate and oblate) of quadrupole deformations [24]. Using this, hereunder points are considered to address the dynamics of $Z_{CN}=104-113$ nuclei, which include: (i) the importance of deformation effects and the role of hot and cold optimum orientations for the decay of different superheavy nuclei. (ii) analysis of optimal reaction partners for the synthesis of superheavy compound systems. (iii) the role of excitation energy and non-sticking MOI (I_{NS}) for $1n$ -decay of various superheavy nuclei.

Extending above study, the decay paths of Dubnium ($Z=105$) nucleus formed in different hot fusion reactions are inspected. This nucleus has been of great interest for last few decades and its first signature was reported by JINR in the analysis of $^{22}\text{Ne}+^{243}\text{Am}$ reaction [25]. Subsequently, various isotopes of Db were synthesized in hot and cold fusion reactions. The excitation functions for the $1n$ and $2n$ exit channels of the $^{208}\text{Pb}(^{51}\text{V}, xn)^{259-x}\text{Db}$ and $^{209}\text{Bi}(^{50}\text{Ti}, xn)^{259-x}\text{Db}$ reactions were measured at LBNL [26]. In addition to this, the capture and fusion

processes were also obtained for $^{259}\text{Db}^*$ and $^{265}\text{Db}^*$ nuclear systems, respectively formed in $^{50}\text{Ti}+^{209}\text{Bi}$ [27] and $^{27}\text{Al}+^{238}\text{U}$ [28] reactions. To have a comprehensive knowledge about the decay of Db-nuclei, recently $^{248}\text{Cm}(^{19}\text{F}, xn)^{267-x}\text{Db}$ and $^{249}\text{Bk}(^{18}\text{O}, xn)^{267-x}\text{Db}$ reactions were compared by Haba *et al.* [29] for the production of Db-isotopes through $4n$ and $5n$ emissions, and the same are tested here in DCM. The individual excitation functions for ^{263}Db and ^{262}Db nuclei are evaluated across the Coulomb barrier energies. The channel cross sections are calculated for both I_S and I_{NS} approaches, by including the quadrupole (β_{2i}) deformations and hot-optimum orientations. The $4n$ channel could be addressed via I_S and I_{NS} approaches, whereas non-sticking (I_{NS}) approach seems favorable to address the $5n$ cross-sections, particularly for $^{18}\text{O}+^{249}\text{Bk}$ reaction.

The layout of chapter is as follows. The calculation and results are discussed in Section 3.2. The conclusion and summery is briefed in Section 3.3.

3.2 Calculations and Results

The work based on neutron evaporation study represented in this chapter is divided into two subparts. In Section 3.2.1, the results are presented for the $1n$ -decay of superheavy nuclei formed via cold fusion reactions (listed in Table 3.1). For decay analysis, the fragmentation potential and preformation probabilities of $Z_{CN}=104$ -109 nuclei are studied at comparable excitation energy $\sim 15\pm 1$ MeV. Additionally, the dynamics of these reactions is analyzed at energies around Coulomb barrier so that a complete picture of the cold fusion reactions, governed through $1n$ -decay be accessed. Next, the explicit role of I_{NS} is also explored to fit the data of higher- Z nuclei ($Z_{CN}=110$ -113), as the decay cross-sections for these nuclei could not be addressed using sticking approach. Section 3.2.2 presents the evolution of $^{267}\text{Db}^*$ nuclear system formed in $^{19}\text{F}+^{248}\text{Cm}$ ($\eta=0.857$) and $^{18}\text{O}+^{249}\text{Bk}$ ($\eta=0.865$) reactions, and an endeavour is made to investigate the neutron evaporation residue cross-sections to have a comprehensive idea of the dynamics involved.

SECTION 3.2: CALCULATIONS AND RESULTS

Table 3.2: DCM calculated fission barrier heights (B_f) and neutron separation energies (S_{1n}) for $Z_{CN}=104-113$ nuclei, formed in ^{208}Pb and ^{209}Bi -induced cold fusion reactions.

Z_{CN}	E_{CN}^* (MeV)	B_f (MeV)	S_{1n} (MeV)
104	15.37	7.660	5.558
105	15.00	7.675	5.883
106	15.92	7.467	6.066
107	14.20	7.554	6.019
108	15.62	7.093	6.080
109	15.30	7.000	6.230
110	15.80	6.230	7.310
111	14.80	6.187	7.280
112	15.00	5.099	7.202
113	14.10	4.969	7.283

3.2.1 Dynamics of $1n$ emission in Pb and Bi induced reactions

The withdrawal from the well studied cold fusion phenomenon for the synthesis of superheavy systems, lies in the fact that the channel cross-sections diminishes rapidly with increment in charge number of the nucleus. Hence, the cold synthesis process is limited upto $Z=113$. The reason for the decrement of channel cross-sections be found in increasing Coulomb factor. Also, within the cold interaction process, neutron deficient SH nuclei are produced which are far from the closed shells or sub-shells. In order to understand this, it would be interesting to calculate the fission barrier heights (B_f) and neutron separation energies (S_{1n}) of the $Z_{CN}=104-113$ nuclei in DCM. In this work, the fission barrier height is obtained via sum of macroscopic component, calculated by using the LDM and microscopic shell-correction energy (*i.e.* $B_f=B_{LDM}+\delta U \exp(-T^2/T_0^2)$) of deformed nuclear system. Table 3.2 presents the magnitude of B_f , lying in the range $\sim 4.96 - 7.66$ MeV, for $Z_{CN} = 104-113$ superheavy systems. Precise overview of these tabulated values

show lower magnitude of the fission barriers for the higher-Z nuclei, indicating the dominance of fission for these nuclei. Although the magnitude of fission barrier height (B_f) is not varying much, but it effects the overall dynamics of the reactions significantly. Note the theoretical calculations of the fission barriers is a tedious task, as it involves many body quantum problem. As the exact estimation is difficult, so the calculated fission barrier heights (B_f) within different modern approaches [30,31] differ significantly. In addition to the theoretical methodologies, the experimental verification of fission barrier is also challenging as the superheavy nuclear systems are characterized by small decay half-lives. Hence in view of this, one neutron separation energies (S_{1n}) are also calculated through DCM, which lie in the range of 5.55 to 7.28 MeV. Opposite to fission barrier, the neutron separation energy (S_{1n}) increases with increase in Z, hence clearly illustrates that for higher Z-nuclei, the emission of neutron becomes difficult as more energy is required to remove neutron from nucleus. If one compares the B_f and S_{1n} , then it is clear that with increase in charge of nuclei, the height of fission barrier decreases but neutron separation energy increases, resulting in the fact that for higher Z, fission starts dominating over neutron evaporation in cold fusion reactions. As a consequence of this, lower magnitude of cross-sections and low formation probabilities are obtained for neutron evaporation corresponding to higher-Z nuclei.

Within the interplay of the neutron emission and fission, the focus of this work is to address the $1n$ cross-sections of $Z_{CN} \geq 104$ SHN formed in the cold fusion process. In order to achieve this, the calculations for the $1n$ -decay are performed with spherical as well as for the deformed choices of the fragmentation in the fixed energy range of 15 ± 1 MeV. Starting with the calculated fragmentation potentials $V(A_2)$ for spherical nuclei, an attempt is made to fit the experimental data. The decay cross-sections of $Z_{CN}=104-106$ nuclei show decent agreement with the experimental findings but σ_{1n} for $Z_{CN} > 106$ show deviation using spherical fragmentation approach. Table 3.3 is presented here for the calculations of σ_{1n} , fitted for the spher-

SECTION 3.2: CALCULATIONS AND RESULTS

Table 3.3: Comparison of experimental [8, 16–23] and DCM calculated $1n$ cross-sections (σ_{1n}) of $Z_{CN}=104$ -109 nuclei, by including spherical as well as deformed choices of fragmentation at $\ell = \ell_{max}$.

Z_{CN}	E_{CN}^* (MeV)	Temperature (MeV)	(Sph)		(β_{2i}) - deformed		ℓ_{max}		$\sigma_{Exp.}$ (nb)
			ΔR	σ_{DCM}	ΔR	σ_{DCM}	sph	β_{2i}	
			(fm)	(nb)	(fm)	(nb)	($\hbar$)	($\hbar$)	
104	15.37	0.830	1.641	42.90	1.635	42.60	107	96	43.00^{+10}_{-8}
105	15.00	0.819	1.670	2.550	1.841	2.480	97	90	$2.500^{+0.72}_{-0.55}$
106	15.92	0.841	1.545	0.220	1.515	0.226	98	94	$0.226^{+0.14}_{-0.10}$
107	14.20	0.791	2.000	0.051	1.716	0.259	67	80	$0.260^{+0.20}_{-0.12}$
108	15.62	0.824	1.950	0.003	2.007	0.045	66	78	$0.045^{+0.01}_{-0.01}$
109	15.30	0.814	1.900	0.0003	1.705	0.006	60	76	$0.006^{+0.005}_{-0.002}$

ical and deformed fragmentation choices. This table clearly shows that only $Z_{CN}=104$, 105, and 106 nuclei fit the data, whereas for higher superheavy nuclei there is considerable difference in the calculated and measured values of σ_{1n} is obtained for the use of spherical fragmentation. Specifically, this difference increases with Z-number of the decaying nuclei. To overcome this, the deformations are included upto β_{2i} , allowing the optimum orientations (θ_i^{opt}). The deformed fragmentation leads to a nice comparison of experimental [8, 16–23] and DCM based calculations at comparable energies (see Table 3.3). Hence in view of above, one can realize the importance of deformations for the cold-fusion reactions, as the deformation effects seem highly desirable to understand the dynamics of $Z_{CN}>106$ nuclei within the DCM approach. Similar results was extracted for the hot fusion processes, i.e. the deformations of the fragments are essential to address the decay of nuclei formed in the hot fusion reactions [12, 13].

Further, the explicit role of collision orientations on the formation of cold compound nuclei is explored. By including the effects of deformations and orientations, the fragment profiles or potential energy surfaces (PES) are plotted for composite systems. Note that within the deformed approach, one can use cold (non-compact)

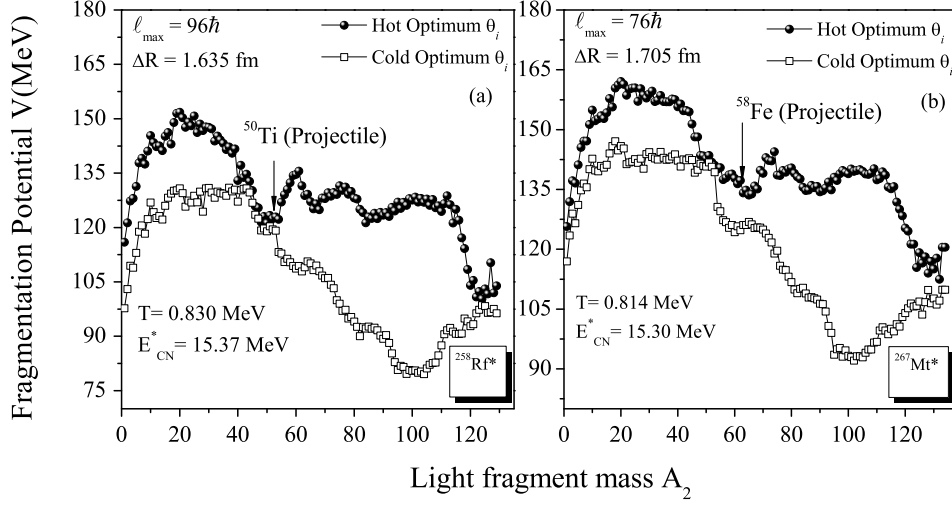


Figure 3.1: Variation of fragmentation potential as a function of light fragment mass for the hot and cold orientations of the fragments, plotted at $\ell = \ell_{max}$ values for (a) $^{258}\text{Rf}^*$ and (b) $^{267}\text{Mt}^*$ nuclei at fixed magnitude of neck-length parameters (ΔR), best fitted for hot orientation approach.

and hot (compact) configurations, which are obtained as optimum orientations with ‘lowest barrier and largest radius’ and ‘highest barrier and smallest radius’ as explained in Chapter 2. To opt the favorable orientation approach for the superheavy nuclei, the comparison of hot and cold optimum orientations is made in the DCM framework at the fixed magnitude of neck-length parameter (ΔR), fitted for the hot orientation approach. Fig. 3.1 presents the fragmentation profiles for $^{258}\text{Rf}^*$ ($Z_{CN} = 104$) and $^{267}\text{Mt}^*$ ($Z_{CN} = 109$) nuclei for hot and cold orientations. An overview of this figure reveals a fact that the explicit minima(s) at the target-projectile combinations are found near ^{50}Ti and ^{58}Fe , respectively for $^{258}\text{Rf}^*$ and $^{267}\text{Mt}^*$ nuclei, and are clearly visible for hot optimum approach. Such minima(s) corresponding to entrance channel mass asymmetry are absent for the use of cold optimum orientations. In QMFT, it is assumed that the t-p combinations which are on the minima of potential energy surface (PES), end up with the formation of compound nucleus [32]. Also for each compound nucleus, the deep minima(s) in potential energy surface, which are related to shell effects, occur at few (t, p) combinations and corresponding

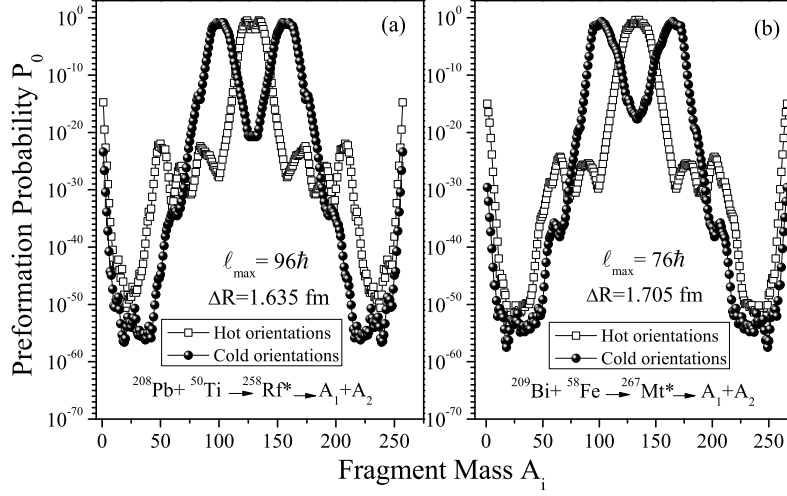


Figure 3.2: Same as Fig. 3.1, but plotted for preformation probability (P_0) corresponding to the neck-length parameters (ΔR), best fitted for hot optimum orientations.

η -values. Any change in η -value is associated with nuclear shape, hence effects the stability of the system. This may be due to the fact that for central collisions, if the compound system reached along the minima in the potential, the excitation would be minimum and system would be more stable for corresponding η -states. In view of above discussion, the use of hot optimum orientations seems to be more suitable as compare to that for the cold non-compact configurations of the fragments.

In support of above discussion, Fig. 3.2 is plotted to show the distribution of preformation probability (P_0) of various outgoing fragments within $^{258}\text{Rf}^*$ and $^{267}\text{Mt}^*$ nuclei for the hot and cold orientation approaches. One should note that P_0 is the probability of formation of outgoing cluster or fragment within compound system. Elaborating this, if the magnitude of P_0 is higher for evaporation residues (ER) then the system probably undergo ER-decay after the formation of stable compound system and if P_0 value of fission region is higher then there is possibility of fission. For comparing the preformation profiles, the calculations with the cold orientations are done at the same ΔR and ℓ_{max} values, as taken for hot orientation approach. It is observed that (i) the magnitude of P_0 for neutron evaporation channels is higher

for hot optimum orientations as compared to cold one. (ii) A symmetric hump is observed in case of hot optimum orientations for $^{258}\text{Rf}^*$ and $^{267}\text{Mt}^*$ nuclei which favor the symmetric fission after the formation of compound nucleus against quasi-fission. (iii) the preformation probability of the symmetric fission fragments reduces by a significant amount when hot orientations are substituted by cold optimum configurations of the fragments, which means that hot orientations prefer symmetric fission and the cold orientations exhibit asymmetric fragmentation, as depicted from Fig. 3.2(a) and (b). It is clearly visualized that the distribution of P_0 is unique for the specific fragment range for hot and cold optimum orientations. Elaborating this, the collective clusterization technique in the DCM framework reinforces the preformation probability to contribute mainly towards the neutron evaporation and fission regions for hot-compact configurations of fragments. On the other hand, the preformation probability for cold-orientation approach is characterized mainly by asymmetric distribution among heavy mass fragments (HMFs), and hence becomes the reason for the reduction of the preformation factor for the neutron evaporation and fission channels. Due to lower preformation probability for cold orientations, the $1n$ -channels are underestimated by significant amount for $Z_{CN}=104-109$ nuclei, and the calculated cross-sections do not match with the available experimental data [8, 16–23]. However, the use of hot optimum orientations of β_{2i} -deformed nuclei seems to work nicely for the $1n$ -decay channels for majority of superheavy nuclei ranging $Z_{CN}=104-109$. Therefore, further calculations are carried out by using β_{2i} -deformed fragmentation within hot orientation criteria alone. Here, note that the cross-sections of $Z_{CN}=110-113$ could not be addressed within this approach, details of which are discussed later.

The optimal choice of entrance channel in the formation of superheavy nuclei plays extremely eminent role to understand the interaction process of such massive nuclei. Especially in the formation of SHN, where the probability of complete fusion leading to the compound nucleus formation is feeble, the appropriate choice of targets and projectiles is highly desirable. In view of this, subsequent analysis is

SECTION 3.2: CALCULATIONS AND RESULTS

Table 3.4: Target-projectile combinations (A_1 , A_2) referring to potential energy minima in Fig. 4 for “hot optimum” orientations of various studied reactions and their characteristic properties at $\ell=\ell_{max}$.

Z	Reaction	η	V_B	R_B	Z	Reaction	η	V_B	R_B
	A_1+A_2		(MeV)	(fm)		A_1+A_2		(MeV)	(fm)
$^{258}_{104}\text{Rf}$	$^{13}\text{C}+^{245}\text{Cf}$	0.899	99.067	11.35	$^{259}_{105}\text{Db}$	$^{13}\text{C}+^{246}\text{Es}$	0.899	95.802	11.40
	$^{22}\text{Ne}+^{236}\text{Pu}$	0.829	133.882	11.55		$^{22}\text{Ne}+^{237}\text{Am}$	0.830	131.557	11.60
	$^{26}\text{Mg}+^{232}\text{U}$	0.798	151.028	11.60		$^{26}\text{Mg}+^{233}\text{Np}$	0.798	149.063	11.60
	$^{32}\text{Si}+^{226}\text{Th}$	0.751	162.724	12.00		$^{32}\text{Si}+^{227}\text{Pa}$	0.752	161.303	12.00
	$^{40}\text{Ar}+^{218}\text{Rn}$	0.689	187.432	12.40		$^{48}\text{Ca}+^{211}\text{At}$	0.629	197.051	12.65
	$^{48}\text{Ca}+^{210}\text{Po}$	0.627	197.055	12.65		$^{50}\text{Ti}+^{209}\text{Bi}$	0.613	210.637	12.60
	$^{50}\text{Ti}+^{208}\text{Pb}$	0.612	210.174	12.65		$^{68}\text{Ni}+^{191}\text{Ir}$	0.474	244.937	12.55
	$^{68}\text{Ni}+^{190}\text{Os}$	0.472	243.890	12.30		$^{84}\text{Se}+^{175}\text{Lu}$	0.351	273.858	12.40
	$^{84}\text{Se}+^{174}\text{Yb}$	0.348	272.330	12.35		$^{114}\text{Cd}+^{145}\text{La}$	0.119	304.023	12.55
	$^{114}\text{Cd}+^{144}\text{Ba}$	0.116	300.572	12.55		$^{122}\text{Sn}+^{137}\text{Xe}$	0.057	295.530	13.10
	$^{124}\text{Sn}+^{134}\text{Xe}$	0.038	292.092	13.10					
$^{260}_{106}\text{Sg}$	$^{12}\text{C}+^{248}\text{Fm}$	0.907	99.693	11.25	$^{263}_{107}\text{Bh}$	$^{13}\text{C}+^{250}\text{Md}$	0.893	89.498	11.50
	$^{22}\text{Ne}+^{238}\text{Cm}$	0.769	134.633	11.60		$^{22}\text{Ne}+^{241}\text{Bk}$	0.832	127.904	11.65
	$^{26}\text{Mg}+^{234}\text{Pu}$	0.800	152.531	11.60		$^{26}\text{Mg}+^{237}\text{Am}$	0.802	146.086	11.65
	$^{32}\text{Si}+^{228}\text{U}$	0.753	165.030	11.95		$^{32}\text{Si}+^{231}\text{Np}$	0.756	159.993	12.00
	$^{48}\text{Ca}+^{212}\text{Rn}$	0.630	200.218	12.65		$^{48}\text{Ca}+^{215}\text{Fr}$	0.634	196.941	12.70
	$^{50}\text{Ti}+^{210}\text{Po}$	0.615	213.776	12.65		$^{50}\text{Ti}+^{213}\text{At}$	0.619	210.749	12.70
	$^{52}\text{Cr}+^{208}\text{Pb}$	0.600	213.833	12.60		$^{54}\text{Cr}+^{209}\text{Bi}$	0.589	225.573	12.50
	$^{70}\text{Zn}+^{190}\text{Os}$	0.461	260.031	12.50		$^{70}\text{Zn}+^{193}\text{Ir}$	0.467	257.023	12.60
	$^{86}\text{Kr}+^{170}\text{Yb}$	0.323	286.274	12.40		$^{86}\text{Kr}+^{177}\text{Lu}$	0.346	284.626	12.45
	$^{122}\text{Sn}+^{138}\text{Ba}$	0.061	301.520	13.10		$^{124}\text{Sn}+^{139}\text{La}$	0.057	301.956	13.15
$^{266}_{108}\text{Hs}$	$^{22}\text{Ne}+^{244}\text{Cf}$	0.834	128.274	11.65	$^{267}_{109}\text{Mt}$	$^{22}\text{Ne}+^{245}\text{Es}$	0.838	128.389	11.65
	$^{26}\text{Mg}+^{240}\text{Cm}$	0.804	146.652	11.65		$^{26}\text{Mg}+^{241}\text{Bk}$	0.805	146.983	11.60
	$^{36}\text{S}+^{230}\text{U}$	0.729	176.309	12.10		$^{48}\text{Ca}+^{219}\text{Ac}$	0.640	199.867	12.70
	$^{48}\text{Ca}+^{218}\text{Ra}$	0.639	198.481	12.70		$^{50}\text{Ti}+^{217}\text{Fr}$	0.692	214.060	12.70
	$^{54}\text{Cr}+^{212}\text{Po}$	0.593	226.737	12.60		$^{58}\text{Fe}+^{209}\text{Bi}$	0.565	241.100	12.60
	$^{58}\text{Fe}+^{208}\text{Pb}$	0.563	238.582	12.60		$^{65}\text{Co}+^{202}\text{Pb}$	0.513	242.451	12.85
	$^{72}\text{Zn}+^{194}\text{Pt}$	0.458	263.916	12.30		$^{74}\text{Zn}+^{193}\text{Au}$	0.445	266.513	12.30
	$^{90}\text{Sr}+^{176}\text{Yb}$	0.323	294.077	12.05		$^{128}\text{Te}+^{139}\text{La}$	0.041	311.784	13.20
	$^{114}\text{Cd}+^{152}\text{Nd}$	0.142	316.598	12.50		$^{132}\text{Xe}+^{135}\text{Cs}$	0.011	312.371	13.20
	$^{128}\text{Te}+^{138}\text{Ba}$	0.037	307.061	13.20					

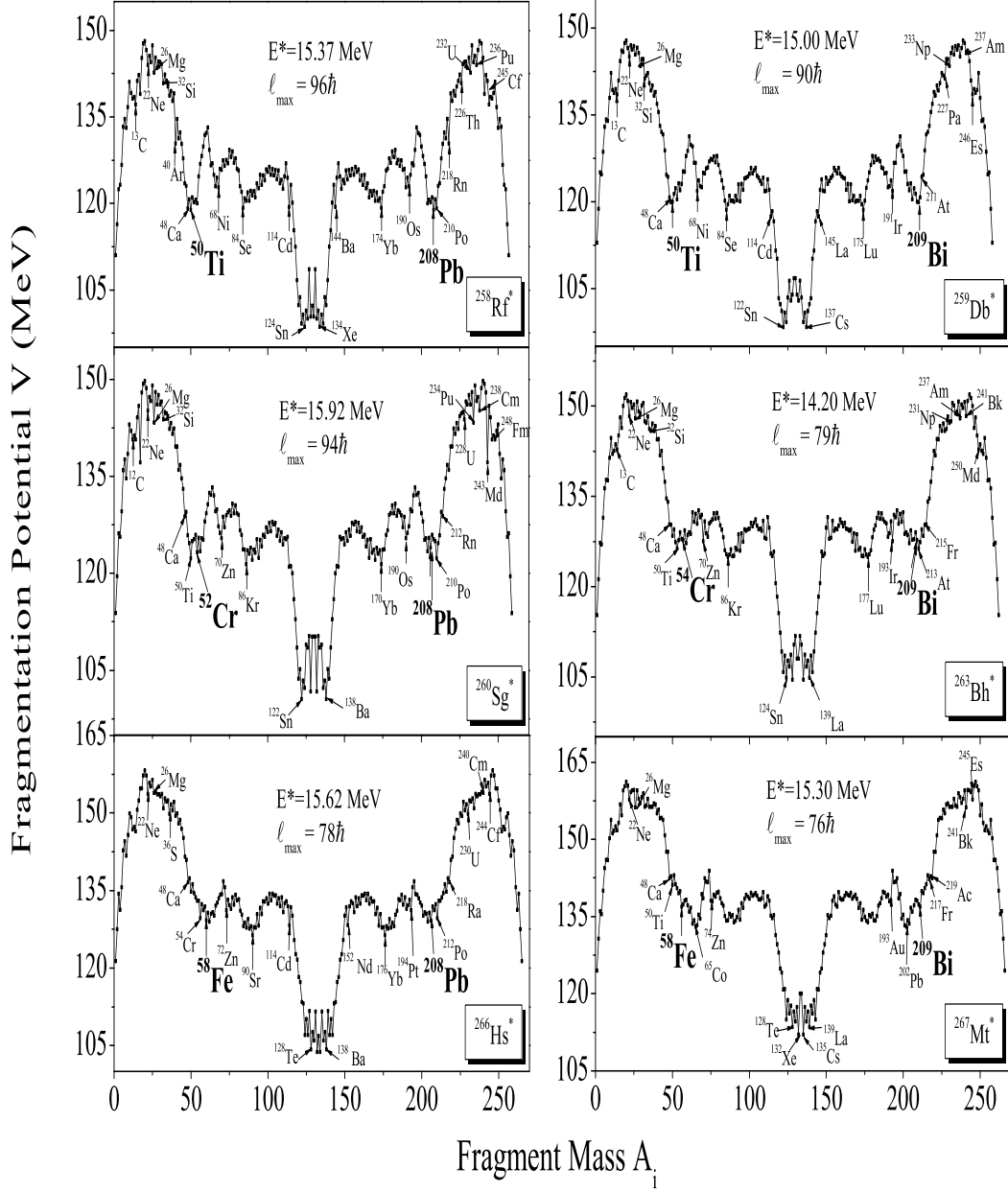


Figure 3.3: Mass fragmentation potentials V (MeV), plotted at $\ell=\ell_{\max}$ for the formation of $Z_{CN}=104-109$ nuclei corresponding to $E_{CN}^*=15 \pm 1$ MeV, having hot optimum orientations and β_{2i} -deformations included for all possible (t,p)-combinations of incoming nuclei. The experimentally verified (t,p)-combinations are shown in boldface.

carried out to address the different (t,p) combinations, required for the formation of $Z_{CN}=104-109$ nuclei. Following Fig. 3.1 and 3.2, the hot optimum orientations are applied to understand the superheavy dynamics, worked out using the QMFT [33–36]. The QMFT provides the theoretical basis for the optimum choice of (t,p) combinations for synthesizing various isotopes of superheavy nuclei. According to this, (t,p) combination lying at the minima of the fragmentation potential exhibit the most suited interaction pair for the formation of the nuclei. The cold fusion synthesis via fragmentation phenomenon was first discussed by Greiner and his collaborators [32]. The importance of this study lies in the fact that the choice of the optimum target-projectile combination leads to the maximum fusion cross-sections, hence the fragmentation potential of the nucleus provides a decent description of the fusion dynamics of heavy ion reactions. In view of this, the fragmentation potentials are calculated for nuclei upto $Z_{CN}=109$. Fig. 3.3 shows the various target-projectile combinations, lying at the minima of fragmentation potential for $Z_{CN}=104-109$ superheavy nuclei. Interestingly, the experimentally studied (t,p) combinations are seen at the minima position, justifying that our analysis is in accordance with experiments. Beside the available (t,p) combinations, QMFT analysis is exploited to give new probable candidates of entrance channels to form compound systems within superheavy mass region. In Fig. 3.3 the fragmentation potentials of $Z_{CN}=104-109$ are plotted at the neck-length parameters fixed for the $1n$ -decay cross-sections, as the location of these minima is independent of the choice of ΔR values [14]. The resulting (t,p) combinations from PES are listed in Table 3.4. In addition to the observed combinations, target-projectile mass asymmetry (η), barrier height (V_B) and barrier position (R_B) are also mentioned in Table 3.4, as these parameters are required to estimate an optimum choice of (t,p) combination for the production of a stable nuclear system. $^{48}\text{Ca}+^{210}\text{Po}$, $^{48}\text{Ca}+^{211}\text{At}$, $^{50}\text{Ti}+^{210}\text{Po}$, $^{50}\text{Ti}+^{213}\text{At}$, $^{54}\text{Cr}+^{212}\text{Po}$, $^{50}\text{Ti}+^{217}\text{Fr}$, and $^{65}\text{Co}+^{202}\text{Pb}$ seems the possible (t,p) combinations for synthesis of $Z_{CN}=104-109$ superheavy nuclei, respectively.

Table 3.5: DCM fitted $1n$ -cross-sections (σ_{1n}) calculated at maximum excitation energies and compared with experimental data [8, 16–23] using sticking moment of inertia (I_S) approach.

Z_{CN}	E_{CN}^* (MeV)	(I_S)		ℓ_{max} I_S ($\hbar$)	$\sigma_{Exp.}$ (nb)	Error bars
		ΔR (fm)	σ_{DCM} (nb)			
104	24.69	1.191	3.79×10^{-1}	117	3.80×10^{-1}	+0.5000 -0.2400
105	20.30	1.398	2.65×10^0	106	2.60×10^0	+1.1900 -0.8500
106	23.20	1.279	1.71×10^{-1}	106	1.70×10^{-1}	+0.2200 -0.1100
107	28.00	1.178	5.66×10^{-2}	115	$< 5.60 \times 10^{-2}$	+0.0000 -0.0000
108	19.82	1.370	2.31×10^{-3}	94	2.23×10^{-3}	+0.0055 -0.0022
109	17.49	1.540	2.50×10^{-3}	83	2.57×10^{-3}	+0.0026 -0.0014
110	19.10	1.544	5.50×10^{-4}	87	5.48×10^{-4}	+0.0032 -0.0000
111	19.17	1.517	1.50×10^{-5}	82	1.41×10^{-5}	+0.0010 -0.0000
112	15.00	1.750	3.22×10^{-7}	56	4.40×10^{-4}	+0.0005 -0.0002
113	14.10	1.650	1.10×10^{-9}	55	5.50×10^{-5}	+0.00015 -0.00004

The above discussion about the $1n$ -decay of $Z_{CN}=104$ -109 superheavy nuclei is carried out at the comparable energies of 15 ± 1 MeV. It is important to mention that the cold fusion reactions induced via ^{208}Pb and ^{209}Bi targets can be used to produce the SHE upto $Z_{CN}=113$, but until now the $1n$ cross-sections upto $Z_{CN}=109$ have addressed, as mentioned in Table 3.3. This may be due to the fact that the σ_{1n} of $Z_{CN}=110$ -113 are perhaps not reinforced through the quadrupole (β_{2i}) deformed fragmentation approach in the energy range 15 ± 1 MeV. Hence to understand the decay of higher Z nuclei, following hierarchy is followed: (i) instead of using the β_{2i} -deformations of the decay fragments, the deformation effects upto β_{4i} are included. (ii) the excitation energy is enhanced to the highest available values [8, 16–23] around the Coulomb barrier, so that the $1n$ cross-sections of $Z_{CN}=110$ -113 could be addressed. (iii) finally the centrifugal part of the fragmentation potential is modified by including the non-sticking approach MOI at the highest available excitation energies.

As mentioned above, the σ_{1n} of $Z_{CN}=110$ -113 superheavy nuclei could not be addressed using β_{2i} fragmentation approach within the energy range 15 ± 1 MeV. Since the decay cross-sections of superheavy nuclei are influenced through many factors

SECTION 3.2: CALCULATIONS AND RESULTS

like deformations, orientations, angular momentum and excitation energies, hence all the factors are tested in the present work to fit the σ_{1n} of $Z_{CN}=110-113$ nuclei. First, the higher order deformations are included upto hexadecapole (β_{4i}) within the use of compact orientations at 15 ± 1 MeV energies, but the cross-sections were not achieved even after the inclusion of β_{4i} -deformations. Next, the cross-sections behavior at relatively higher incident energies and corresponding excitation energies is observed to fit $1n$ evaporation data. The $E_{c.m.}$ for $Z_{CN}=110-113$ nuclei, along with others are chosen around the Coulomb barrier as shown in Table 3.1. At maximum energies, the DCM calculated cross-sections matches well with the experimental data with β_{2i} -deformed fragmentation approach for majority of the superheavy nuclei, as shown in Fig. 3.4(a). At these higher energies, the cross-sections of nuclei upto $Z_{CN}=111$ [16–22] fit the data nicely, but heavier nuclei with $Z_{CN}=112-113$ still show some deviation from available data [8, 23] for $1n$ evaporation cross-sections. It is clear from Fig. 3.4(a) that this deviation in the cross-sections increases exponentially as we go from $Z=112$ to 113. In Table 3.5, for respective nuclei, the maximum excitation energies are mentioned along with DCM fitted cross-sections, ΔR , and maximum angular momentum values. If one makes the comparison of fitted ΔR values for deformed case, discussed in Table 3.2 and 3.5 i.e. for maximum and comparable energies (15 ± 1 MeV), then one can observe that at maximum energies the magnitude of neck-length parameters (ΔR) is lower.

Although at maximum energies the cross-sections are addressed upto $Z_{CN}=111$, but heavier nuclei ($Z_{CN}=112-113$) could not be addressed at highest energies. Note that the experimental $1n$ -decay cross-sections are compared with corresponding calculations of DCM cross-sections. The DCM calculated values underestimate the experimental data which indicate the dominance of other decay modes. This suppression of calculated cross-sections from experimental one is model dependent and is related to the position and height of barrier which results in lower preformation probability and hence lower production of evaporation residues. The reason of this suppression is explained in terms of hinderance in entrance channel as shown in Fig.

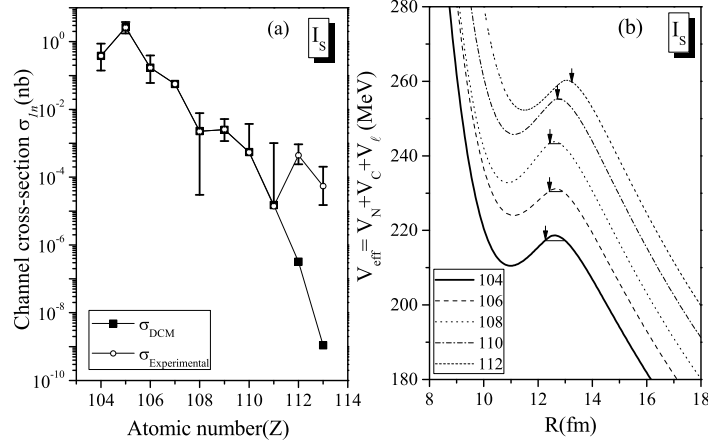


Figure 3.4: (a) Comparison of DCM fitted $1n$ cross-sections with experimental data [8, 16–23] and (b) variation of scattering/effective potential with range (R) using sticking moment of inertia (I_S). These figures are shown at the maximum available energies.

3.4(b), by considering the interaction potential for even- Z nuclei only. The arrows in the figure show the position of the potential at which tunnelling begins i.e. first turning point R_a (as discussed in Chapter 2, Eq. (2.57)). In this figure, scattering potential is plotted as a function of range with respect to the entrance channel of compound nuclei. Interestingly one can observe from Fig. 3.4(b) that, as the charge number of the system increases, the width of the barrier (shown by horizontal line) shrinks and in turn higher R -value are preferred. As a result of this, for a particular target-projectile combination, the composite system goes outside the potential barrier. Due to this, the system disintegrate without forming an equilibrated compound configuration, and fusion does not take place. Hence the compound nucleus formation probability decreases for the nuclei, where the system occurs outside the potential barrier. In view of this, the lower cross-sections of $Z_{CN} > 111$ in Fig. 3.4(a) can be justified.

To resolve this problem one may either increase the incident energy or modify the scattering potential of the chosen systems. As the energy criteria is already exercised in view of [8, 16–23], hence in the subsequent work, an attempt is made to modify the scattering potentials at same energy as mentioned in Table 3.5. Scattering potential

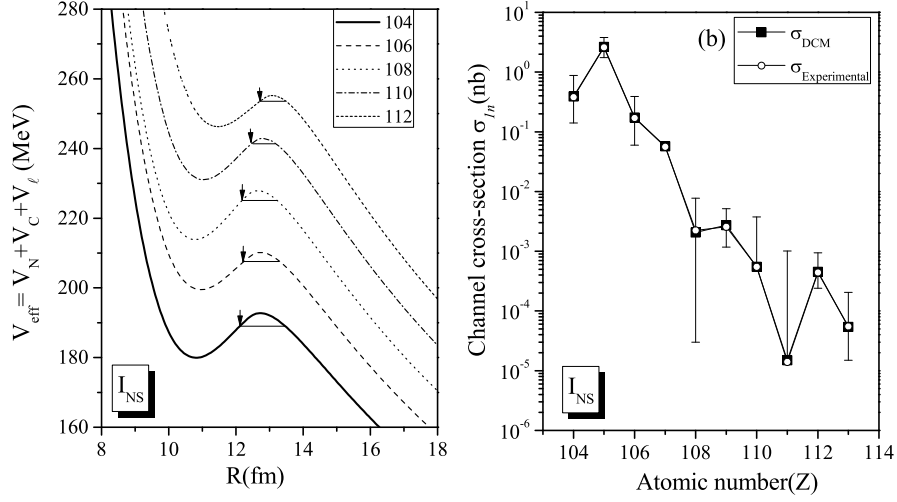


Figure 3.5: Same as Fig. 3.4, but plotted for the non-sticking (I_{NS}) approach of moment of inertia, at maximum reported energies.

is the sum of V_C , V_N , and V_l , and change in any one of these potentials, leads to the modification in potential barrier. Here, the centrifugal part of scattering potential is modified by replacing sticking moment of inertia (I_S) with non-sticking (I_{NS}) one, discussed in Chapter 2, Eq. (2.22) and (2.23). The variation of this modified scattering potential with range is shown in Fig. 3.5(a). It is important to mention that Fig. 3.4(b) is plotted for the sticking MOI (I_S), whereas Fig. 3.5(a) shows the scattering potential of the same nuclei, but plotted for the use of the non-sticking MOI (I_{NS}). A clear overview of Fig. 3.5(a), shows that the barrier gets significantly modified when moment of inertia is changed from sticking limits (I_S) to non-sticking limits (I_{NS}). Although, the width of the barrier becomes compact with increase in charge and mass of nuclei for I_{NS} approach (similar to the results obtain for sticking moment of inertia (I_S)), but the composite system remains within the barrier for higher Z -nuclei as well. Interestingly, the DCM based $1n$ -cross-sections calculated using I_{NS} approach matches well with available data, as shown in Fig. 3.5(b). In other words, the channel cross-sections of $Z_{CN}=112$ and 113 are addressed by adopting I_{NS} . It is important to mention here that Fig. 3.4(b) and 3.5(a) are

Table 3.6: Comparison of experimental [29] and DCM calculated $4n$ and $5n$ -decay cross-sections of $^{267}\text{Db}^*$ nuclear system by including sticking (I_S) and non-sticking (I_{NS}) moment of inertia.

E_{CN}^* (MeV)	Channel	I_S			I_{NS}			$\sigma_{Exp.}$ (nb)
		ΔR (fm)	σ_{DCM} (nb)	$\ell_{max}(\hbar)$	ΔR (fm)	σ_{DCM} (nb)	$\ell_{max}(\hbar)$	
42 ± 1	$^{19}\text{F} + ^{248}\text{Cm}$ ($4n$)	1.730	0.133	121	1.228	0.127	24	0.127
	$^{18}\text{O} + ^{249}\text{Bk}$ ($4n$)	2.471	9.940	102	1.282	9.890	24	10.00
	$^{19}\text{F} + ^{248}\text{Cm}$ ($5n$)	2.188	0.222	101	1.288	0.226	25	0.223
	$^{18}\text{O} + ^{249}\text{Bk}$ ($5n$)	-	-	-	1.303	1.320	25	1.300
47 ± 1	$^{19}\text{F} + ^{248}\text{Cm}$ ($4n$)	1.676	0.064	122	1.200	0.062	24	0.064
	$^{18}\text{O} + ^{249}\text{Bk}$ ($4n$)	1.968	2.030	116	1.249	1.920	25	2.030
	$^{19}\text{F} + ^{248}\text{Cm}$ ($5n$)	2.419	2.020	116	1.288	1.970	26	2.020
	$^{18}\text{O} + ^{249}\text{Bk}$ ($5n$)	-	-	-	1.316	5.770	26	6.010

shown only for even- Z_{CN} nuclei, similar trend is observed for odd- Z_{CN} nuclei which is not shown here to avoid repetition. Hence the use of I_{NS} of the fragments seems more suitable to address the $1n$ -cross-sections of higher Z -superheavy nuclei, formed in the cold fusion reactions.

3.2.2 Evaporation residue cross-sections of $^{267}\text{Db}^*$ nucleus

In this section, the study carried out earlier using I_S and I_{NS} moment of inertia for cold fusion reactions is extended for hot fusion reactions. The evaporation residue cross-sections of $^{267}\text{Db}^*$ nuclear system, formed in $^{19}\text{F} + ^{248}\text{Cm}$ and $^{18}\text{O} + ^{249}\text{Bk}$ reactions are calculated at near barrier energies, using I_S and I_{NS} moments of inertia. Within the I_S -approach, $4n$ cross-sections are addressed nicely as shown in Table 3.6, but the $5n$ -channel of $^{18}\text{O} + ^{249}\text{Bk}$ reaction could not be fitted even at the maximum possible magnitude of ΔR . To address this discrepancy, the fragmentation potential $V(\text{MeV})$ is modified by including the non-sticking (I_{NS}) approach of the moment of inertia, as shown in Fig. 3.6 and Table 3.6. The fragmentation potentials, plotted in Fig. 3.6, are presented at the neck-length parameters (ΔR) of the $4n$ -clusters of $^{267}\text{Db}^*$ nucleus, to obtain the idea about the decay structure. The overview of this figure reveals the fact that structure is significantly modified for the neutron

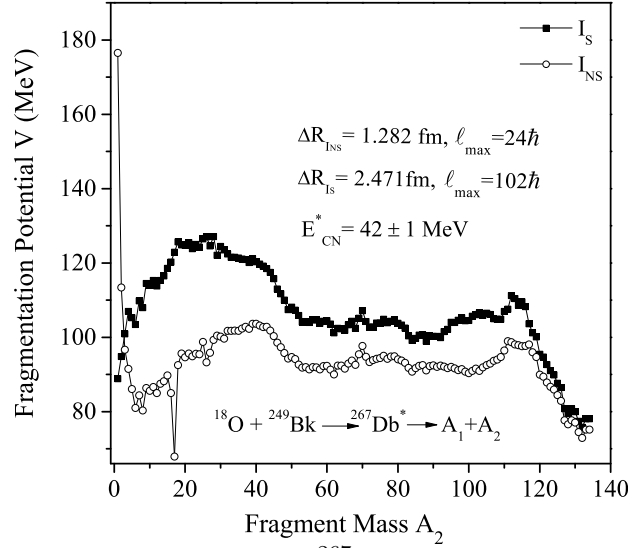


Figure 3.6: Fragmentation potential for $^{267}\text{Db}^*$ nuclear system plotted as a function of light fragment mass A_2 using sticking (I_S) and non-sticking (I_{NS}) limits of moments of inertia.

evaporation region, whereas the intermediate mass, heavy mass, and fission region give similar fragmentation structure for I_S as well as I_{NS} approaches. Due to lower fragmentation potential, the $5n$ cross-sections are achieved at lower neck-length parameter within the use of I_{NS} -approach. The same is true for the $4n$ decay channel. Within I_{NS} approach, the neck length-parameters (ΔR) and $\ell_{\max}$ values are reduced significantly. It is to be noted here that, within I_{NS} limit of moment of inertia, an unexpected minima is observed for ^{17}B fragment which is possibly because of higher deformation ($\beta_2 = -0.398$) of Boron. However, when I_S limit of moment of inertia is considered, the fragment at $A_2 = 17$ is replaced by ^{17}O ($\beta_2 = 0.107$) and hence no such dip is observed here.

Fig. 3.7 is plotted to compare the fragmentation potential, P_0 , and P for $^{18}\text{O} + ^{249}\text{Bk}$ and $^{19}\text{F} + ^{248}\text{Cm}$ reactions. The comparison is made to understand the decay dynamics, particularly in view of the $4n$ and $5n$ clusters of $^{267}\text{Db}^*$ nuclear system. It is relevant to mention here that Figs. 3.7(a),(b), and (c) are plotted for the $4n$ -decay of $^{267}\text{Db}^*$ compound system and the inset shows the same for $5n$ -emission at same energy. Fig. 3.7(a) is presented to obtain the variation of fragmentation

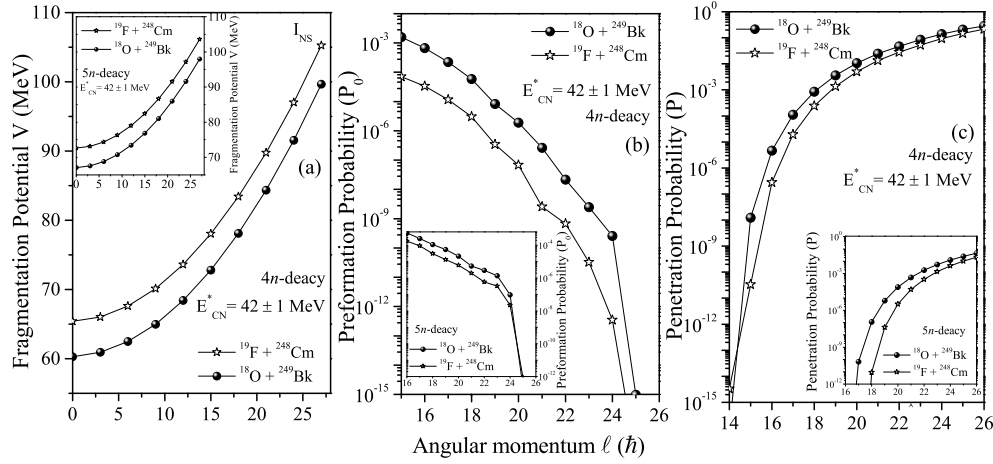


Figure 3.7: Variation of the (a) fragmentation potential V (MeV), (b) preformation probability (P_0), and (c) penetration probability (P) for $^{267}\text{Db}^*$ nucleus formed in $^{19}\text{F} + ^{248}\text{Cm}$ and $^{18}\text{O} + ^{249}\text{Bk}$ reactions, plotted as a function of angular momentum for $4n$ and $5n$ decays.

potential with wide range of angular momentum states for both ^{249}Bk and ^{248}Cm -induced reactions, and it gives lower magnitude for $^{18}\text{O} + ^{249}\text{Bk}$ reaction, leading to the fact that at same excitation energy, the probability of neutron emission ($4n$ or $5n$) is relatively more prompt for this interacting pair. This result is further supported by Figs. 3.7(b) and (c) which show larger magnitude of preformation (P_0) and penetration (P) probabilities for $^{18}\text{O} + ^{249}\text{Bk}$ reaction. Also, among $4n$ or $5n$ -emission, the probability of $5n$ -decay is relatively larger. The magnitude of the neck-length parameters reported in Table 3.6 supports the above result as higher magnitude of the neck-length parameters are reported for the $5n$ -emission within the I_{NS} approach. Larger neck leads to easier splitting of the cluster from the excited nucleus. Hence one may conclude that probability of neutron emission is higher for the nucleus formed in $^{18}\text{O} + ^{249}\text{Bk}$ reaction and out of $4n$ and $5n$ emission, $5n$ -decay is relatively more prompt.

3.3 Conclusions

The DCM is used to describe the production and decay of cold fusion reactions. The fusion dynamics and σ_{1n} in cold fusion reactions are investigated. The production

of heavy fissile nuclei in massive fusion reactions is very complicated, involving certain quantities that influence the dynamical evolution. So, the applicability of deformation and orientation degree of freedom is worked out in relevance to the potential energy surfaces to understand the fusion mechanism and found that hot orientation criteria performs better to address the chosen fusion reactions within DCM approach, as the potential energy minima appear at (t,p) combinations for these configurations. Also the other possible (t,p) combinations that favor stable systems are analyzed, which include ^{50}Ti , ^{54}Cr , ^{48}Ca and ^{65}Co projectiles as possible choices. Furthermore, the $1n$ channel cross-sections of the ^{208}Pb and ^{209}Bi induced cold fusion reactions are calculated. With the inclusion of the deformations effects upto β_{2i} , σ_{1n} of $Z_{CN}=104-109$ nuclei fit the experimental data nicely. In order to address the cross-sections of $Z_{CN}=110-113$ SHN, the role of I_{NS} is exercised. Finally, the channel cross-sections of all the nuclei i.e. $Z_{CN}=104-113$ are fitted within the non-sticking approach of the MOI. However, the sticking (I_S) approach leads to the fitting of cross-sections upto $Z_{CN}=111$. Hence the use of I_{NS} seems better to address the $1n$ -decay of heavier superheavy nuclei.

Finally, the $4n$ and $5n$ evaporation residue cross-sections are calculated for $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions using sticking (I_S) and non-sticking (I_{NS}) approaches of the moments of inertia. The $4n$ cross-sections for both reactions are addressed nicely within the I_S and I_{NS} approaches, whereas only non-sticking moment of inertia could address the $5n$ cross-sections of $^{18}\text{O}+^{249}\text{Bk}$ reaction. Further, the fragmentation analysis of the $4n$ and $5n$ decays support prompt emission of $5n$ clusters.

After analysing the neutron evaporation dynamics of superheavy nuclei in this chapter, the properties of fission fragments in this mass region will be worked out in chapter 4.

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Chapter 4

Fission dynamics of various even mass superheavy nuclei

In the former chapter, neutron decay of superheavy nuclei formed via hot and cold fusion reactions was investigated. The $1n$ excitation functions of $Z=104-113$ nuclei formed via ^{208}Pb and ^{209}Bi induced reactions were addressed within DCM framework. This nucleon evaporation study was worked out extensively for $Z=105$ superheavy nucleus formed via hot fusion reactions. It is clear from the literature that, in superheavy nuclei, the fission components contributes significantly in capture process relative to evaporation and hence hinder the formation of stable evaporation residues (ER's). So, here in the current chapter, the insistence is on the study of different aspect of fission dynamics. A comprehensive investigation of CN and nCN processes is worked out in terms of various reaction parameters for $Z=104-120$ superheavy nuclei. A brief introduction of the chapter is given below followed by calculations and discussions.

4.1 Introduction

The formation of superheavy nuclei differ significantly from the lighter mass region where fusion generally occurs after the capture stage [1]. This is by dint of increasing

Coulomb repulsion between interacting massive nuclei in superheavy mass region that can lead to the decay of composite nuclear system before it reaches a compact state. In other words, the reaction partners do not evolve inside the fission saddle, but re-separate after the nucleon transfer. Under such circumstances quasi-fission, quasi-elastic, and deep-inelastic events come into picture, hindering the compound nuclear formation [1–5]. The mass and TKE-distribution of the reaction products actually differentiates between these competing processes. The reaction products with masses similar to projectile and target are associated with the quasi-elastic and deep-inelastic events. Moreover, the asymmetric quasi-fission is observed when the potential energy surfaces (PES) show peaks near the doubly magic Lead (Pb) and its complementary fragments [1–5]. In addition to the asymmetric quasi-fission, mass symmetric events can also be originated through such channels [2, 4, 5]. Broadly speaking, the symmetric fragment distribution can be detected for both CN and nCN processes. In the symmetric compound nucleus decay, the fission is followed by the complete fusion process (termed as fusion-fission or compound nuclear fission), whereas in symmetric non-compound nucleus decay process the target-projectile combination does not pass through the fusion valley, and relatively relaxed decay events (symmetric quasi-fission) are reported as compared to asymmetric quasi-fission process [2,4,5]. The relative contribution of aforementioned processes towards total cross-section is influenced by various factors like Coulomb barrier, Coulomb factor, deformations, orientations, excitation energy, angular momentum *etc.* In terms of these parameters, the distinction between the compound nuclear fission (CN-fission), also termed as fusion-fission, and symmetric quasi-fission events is the ongoing quest for better understanding of related nuclear dynamics. So to understand the fusion process of superheavy nuclei, one can alternatively use the subsequent dynamics of reaction partners.

Owing to above discussion, the importance of mass fragmentation and TKE distribution can be realized, which can further be used to study the decay profile of

considered superheavy nuclei. The application of DCM [6–15] to distinguish between such processes was first carried out for $^{268}\text{Sg}^*$ [11] and $^{278,286}112^*$ [12] nuclei, in which above barrier reaction dynamics was handled through the equatorial interactions of the colliding nuclei and below barrier interactions were addressed for the use of polar interactions. Also, $^{48}\text{Ca}+^{238}\text{U}\rightarrow^{286}112^*$ reaction [7, 8] alongwith $^{48}\text{Ca}+^{248}\text{Cm}\rightarrow^{296}116^*$ [13] were studied in DCM framework to address the magicity criteria of superheavy elements. These works led to the prediction that $Z=126$ and $N=184$ magic closures are suitable to examine the neutron evaporation data [7, 13]. However, magic shell $Z=120$ was suggested to be equally probable for fusion-fission process [8]. In addition to the above reactions, $^{48}\text{Ca}+^{244}\text{Pu}\rightarrow^{292}114^*$ was also investigated to realize the dynamics of the superheavy mass region via neutron evaporation emission, fusion-fission and quasi-fission processes [14, 15].

The present analysis is carried out to extend the above work, so that a comprehensive picture be extracted for $Z=112, 114$, and 116 superheavy systems. The motive of this work is: (i) to make the comparative analysis of decay patterns for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei at comparable excitation energy ~ 39 MeV, (ii) addressal of CN-fission (or fusion-fission) and quasi-fission (symmetric and asymmetric) processes, and (iii) to study the TKE-distribution of the decay fragments. In order to address these points, the fusion-fission and quasi-fission cross-sections for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei lying in $E_{CN}^*=32\text{--}40$ MeV are calculated. In the experimental work [5], the capture cross-sections are measured as: $\sigma_{\text{capture}} = \sigma_{FF} + \sigma_{ER} + \sigma_{QF}$, and the endowment of σ_{ER} is negligible. In addition to this, the individual estimates of fusion-fission (FF) and quasi-fission (QF) cross-sections are also given. The FF component is calculated by considering the symmetric mass fragments of the potential energy surfaces (PES). On the other hand, quasi-fission contribution corresponds to both asymmetric and symmetric mass split. The decay trajectories appearing around Tin (Sn) nucleus are considered to account the symmetric quasi-fission, whereas the asymmetric quasi-fission is addressed via

emergence of the peaks around lead (Pb) and its complementary fragments.

Inclusive of above, the mass and energy distribution of fission like fragments formed in ^{238}U -induced reactions with ^{36}S , ^{48}Ca , ^{48}Ti , and ^{64}Ni projectiles studied at FLNR [16] are also investigated. The following aspects are investigated in this chapter: (i) information about different decay channels is extracted by analyzing the behavior of fragmentation potential and preformation probability, (ii) the role of hot and cold optimum interactions are examined via fission mass distribution of $Z=108$ -120 superheavy nuclei, and (iii) properties like entrance channel mass asymmetry, Coulomb factor (Z_1Z_2), deformations, orientation degree of freedom *etc* are analyzed to have a comprehensive idea of the competing decay mechanisms in fission region.

The calculations and results are described in Section 4.2, followed by the respective conclusions in Section 4.3.

4.2 Calculations and Results

In the first section (i.e. Section 4.2.1) of this chapter, the calculations of σ_{FF} and σ_{QF} are discussed. In addition to this, the potential energy surfaces (PES) (equivalently fragmentation potentials) of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei are compared at above barrier energy ($E^*_{CN} \sim 39$ MeV). The fragmentation and preformation profiles give the detailed decay analysis of $Z=112$, 114, and 116 nuclei. In the second part of this work, DCM is utilized to study the $\overline{TK\overline{E}}$ distributions in reference to the data of [5]. Here, different versions of proximity potentials [17–19] namely Prox-77, Prox-88, and Prox-00 are employed for better description of $\overline{TK\overline{E}}$ -distribution. The role of angular momentum as well as different radii are also explored in the $\overline{TK\overline{E}}$ -analysis of $Z=112$, 114, and 116 nuclei. In Section 4.2.2, calculations with respect to the experimental data of [16] are presented. The different decay mechanisms such as fission ($\frac{A}{2} \pm 20$) and quasi-fission are explored for $^{36}\text{S} + ^{238}\text{U} \rightarrow ^{274}\text{Hs}^*$, $^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}\text{Cn}^*$, $^{48}\text{Ti} + ^{238}\text{U} \rightarrow ^{286}\text{Fl}^*$, and $^{64}\text{Ni} + ^{238}\text{U} \rightarrow ^{302}120^*$ superheavy nuclei

in terms of fragmentation and preformation probability distributions using hot and cold orientation approaches. Along with this, the preformation yield of nuclei ranging $Z=104-120$ is estimated to account the structural variation of mass distribution.

4.2.1 Fission and TKE analysis of ^{48}Ca -induced reactions

In heavy-ion reactions, the fusion can be understood in term of interplay between conservative and dissipative forces. The nuclei approach each other under the influence of nucleus-nucleus Coulomb interaction. If the initial energy of projectile in center-of-mass system is enough and system has appropriate angular momentum, then there is a probability that the colliding nuclei may overcome the Coulomb barrier and get trapped inside the potential well. This leads to the fully equilibrated compound nucleus stage. On the other hand, if the captured system do not evolve deep in the fusion pocket then quasi-fission process comes into picture. In case of collisions involving heavy nuclei, the complete fusion may not occur immediately and there is a probability of occurrence of other processes. In favor of estimating the contribution of competing processes during the formation of superheavy compound nuclei, P_{CN} for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei are calculated. In DCM, it is calculated as [20]

$$P_{CN} = \frac{\sigma_{CN}}{\sigma_{capture}} = \frac{\sigma_{FF} + \sigma_{ER}}{\sigma_{FF} + \sigma_{ER} + \sigma_{QF}} \quad (4.1)$$

Clearly, P_{CN} gives the probability of CN emergence in total fusion cross sections. If $P_{CN} \sim 1$ then the reaction is considered as CN reaction and its deviation from unity provides a possibility of occurrence of some nCN processes. The DCM calculated P_{CN} comes out to be 0.071, 0.0610, and 0.0420 respectively for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei at $E_{CN}^* = 39$ MeV. These calculated values show reasonable agreement with measured P_{CN} values i.e. 0.051, 0.0656, and 0.0422 of [5]. The indication of $P_{CN} < 1$ in the calculated and measured data shows the

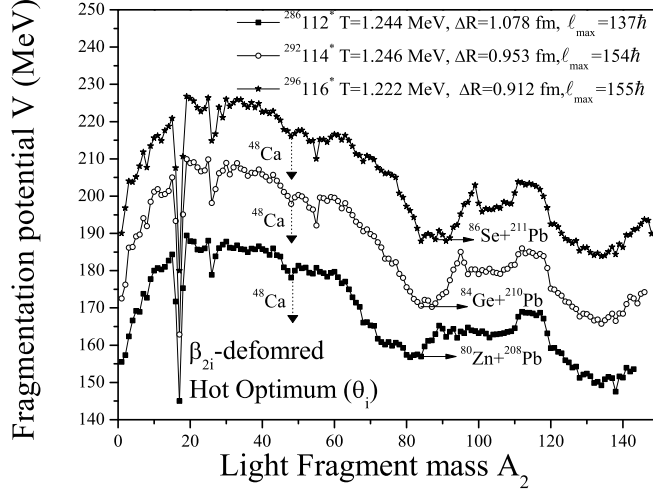


Figure 4.1: Fragmentation potentials minimized in mass coordinate $\eta(A)$ for the decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei, plotted at excitation energy ~ 39 MeV and for highest value of angular momentum $\ell = \ell_{max}$ using the deformed choice of fragmentation.

presence of nCN (QF) processes. The detailed study of fusion-fission and quasi-fission mechanisms is described in subsequent sub-sections.

(i) **Fusion-Fission (FF) and Quasi-Fission (QF) cross-sections of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei:**

Concerning the recent experimental data [5], the FF and QF cross-sections of $Z=112$, 114, and 116 superheavy nuclei are calculated in the framework of DCM [6–15]. The calculations are performed for the deformed choice of fragmentation using hot optimum orientations of the decay fragments for incident energies spread across the Coulomb barrier. The relative decay analysis of $^{286}112^*$, $^{292}114^*$ and $^{296}116^*$ superheavy nuclei is carried out at above barrier energy $E_{CN}^* \sim 39$ MeV. The fragmentation potential is plotted with light fragment mass (A_2) in Fig. 4.1. Following observations can be made from this figure: (i) The magnitude of fragmentation potential is least for the decay of $^{286}112^*$ nucleus and it increases with increase in the Z-number of nuclei, which inturn seem to suggest that decay of $^{286}112^*$ is more probable as compared to $^{292}114^*$, and $^{296}116^*$ nuclei at comparable incident energy. (ii) The magnitude of neck-length parameter is higher for $^{286}112^*$ and least for

SECTION 4.2: CALCULATIONS AND RESULTS

$^{296}116^*$ nucleus. This means that for fixed excitation energies, the decay of $^{286}112^*$ is more prompt as compared to heavier superheavy systems, hence further justifies the above point. (iii) The magnitude of angular momentum is higher for $^{296}116^*$ as compared to $^{292}114^*$ and $^{286}112^*$ nuclei, which may be due to the fact that higher mass requires higher angular momentum for decay. (iv) The heavy mass fragment (HMF) region for the decay of $^{286}112^*$ lies in the range $A_2=70-90$, whereas it gets modified to the higher mass range when the Z-number is changed from $Z=112$ to 114 and 116. (v) Although, for chosen target-projectile combinations (i.e. $^{48}\text{Ca}+^{238}\text{U}$, ^{244}Pu , and ^{248}Cm) there are smaller dips in PES, but the deeper minima is observed across lead (Pb) (and its complementary fragment). So a large mass and charge relocation occur in the direction towards deep minima, as two nuclei start overlapping. During this transmission process, large amount of energy will transfer in the form of excitations and vibrations of the system. Hence there is high probability of quasi-fission in the reactions under consideration. Note that similar observations are noticed for the decay of $Z=112$, 114, and 116 nuclei at below barrier region as well, whose results are not depicted here to avoid the repetition.

The decay analysis of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei can further be elaborated through Fig. 4.2, in which P_0 is plotted with fragment mass A_i ($i=1,2$). This figure can be visualized mainly to address the HMF and fission region. A careful overview of Fig. 4.2 signifies that the peaks in the HMF regions, observed in the decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei are appearing around the lead (Pb) isotopes and their complementary fragments. More precisely, emergence of ^{208}Pb is observed for the decay of $^{286}112^*$ nucleus, however the reactions with heavier targets such as $^{48}\text{Ca}+^{244}\text{Pu}\rightarrow^{292}114^*$ and $^{48}\text{Ca}+^{248}\text{Cm}\rightarrow^{296}116^*$ are associated with the emission of heavier isotope of Pb i.e. ^{210}Pb and ^{211}Pb respectively, which is in accordance with the experimental observation [5]. One may associate these secondary peaks with the possible occurrence of quasi-fission, as also suggested in [1–5]. Due to highly asymmetric nature of these peaks, this process is termed as asymmetric

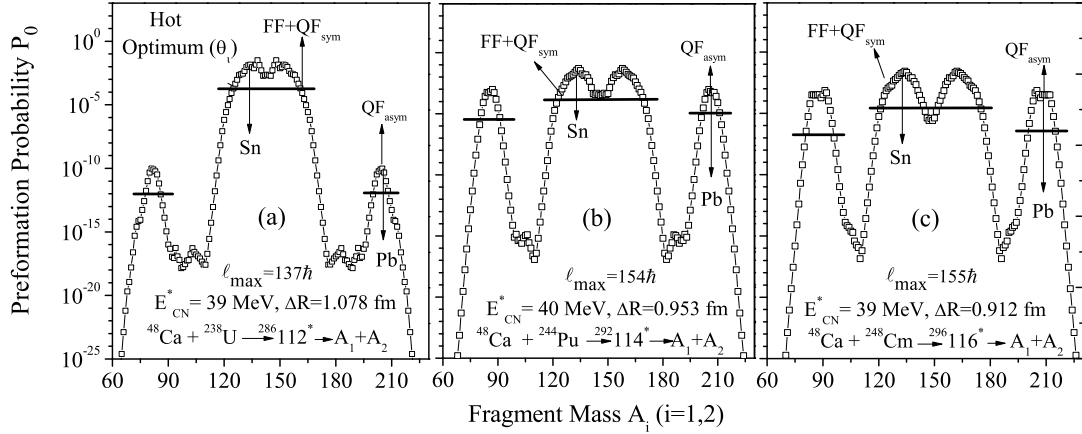


Figure 4.2: Variation of preformation probability with the fragment mass for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ superheavy nuclei, by including the β_{2i} -deformation effects within hot optimum approach, plotted at fixed neck-length parameter and highest value of angular momentum.

quasi-fission in which the fission trajectory is directed towards the Pb-region, prior to the formation of compound state. Consequently, one may assume that the magic shell effects of the decaying nuclei are responsible for the occurrence of such quasi-fission peaks. Hence the relevance for the emergence of HMF dips in the Fig. 4.1 is clearly demonstrated in Fig. 4.2, whose origin can be governed via $Z=82$ magicity.

Fig. 4.2 clearly signifies that the maximum preformation probability is seen for near symmetric fission fragments for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei. These fragments are shown in the Fig. 4.2(a), (b), and (c) respectively by the upper horizontal line. Note that such peaks may not find its origin only in the CN-decay, they are sometimes originated via competing nCN process, such as symmetric QF. It means that the asymmetry feature which is the main characteristic of the quasi-fission may get relaxed and symmetric events in the quasi-fission process may start appearing. The detailed discussion regarding the symmetric and asymmetric quasi-fission is carried out in this work. Additionally, it is clearly evident from Fig. 4.2(b) and Fig. 4.2(c) that the symmetric-fission competes the asymmetric QF process in the decay of $^{292}114^*$ and $^{296}116^*$ nuclei, as the preformation peaks are comparable in the magnitude. On the other hand, the decay of $^{286}112^*$ nucleus is quite different, in which suppression in the magnitude of asymmetric quasi-fission peaks is observed

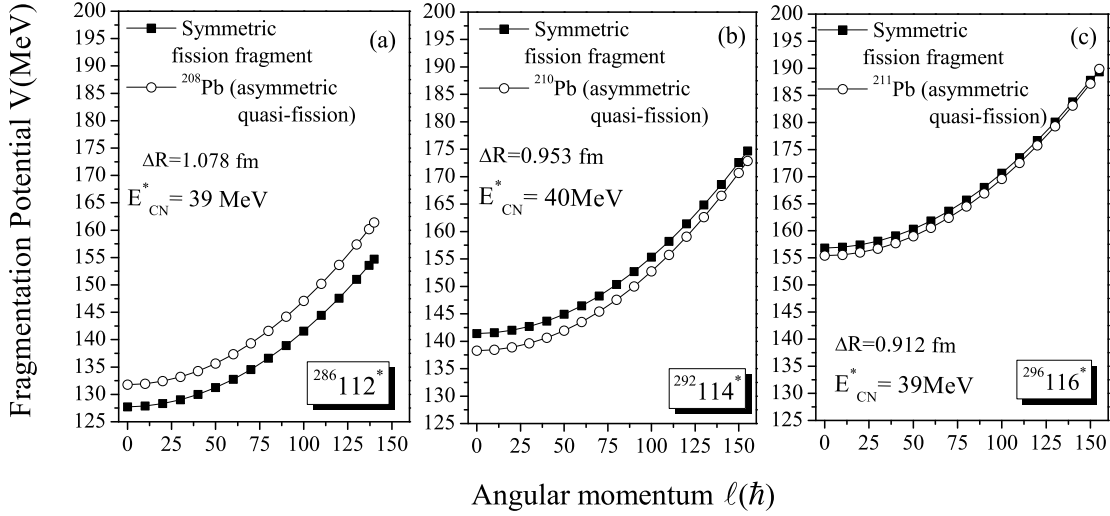


Figure 4.3: Variation of fragmentation potential with the angular momentum for most symmetric fission fragment and Pb-isotopes of asymmetric quasi-fission in the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ nuclei.

as compared to that for $Z=114$ and $Z=116$ nuclei. In terms of broadness, more broader peak is observed in the decay of $^{296}116^*$ followed by $^{292}114^*$ and $^{286}112^*$. This simply implies the effect of entrance channel on the distribution of asymmetric quasi-fission peaks. The height as well as the broadness both increase Z number of the compound nucleus. Similar results are observed for the symmetric-fission peaks exhibiting decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ compound nuclei.

For further investigation of fission and quasi-fission processes, Fig. 4.3 is plotted which shows the variation of the fragmentation potential with ℓ -value for the most symmetric fission fragment and asymmetric quasi-fission fragment (Pb-isotopes). It is evident from the figure that the fragmentation potential for these fragments increases ℓ -values. Fig. 4.3(a) signifies that the fragmentation potential of symmetric fission fragment of $^{286}112^*$ is lower than that of quasi-fission fragments (^{208}Pb), hence the decay of fission fragment is more probable as compared to the fragment associated with the asymmetric quasi-fission process. This result is in accordance with Fig. 4.2 in which symmetric-fission component is dominating as compared to asymmetric quasi-fission component for $Z=112$ nucleus. The decay processes are quite distinguishable for $Z=112$ nucleus, but as Z -number increases, the overlapping

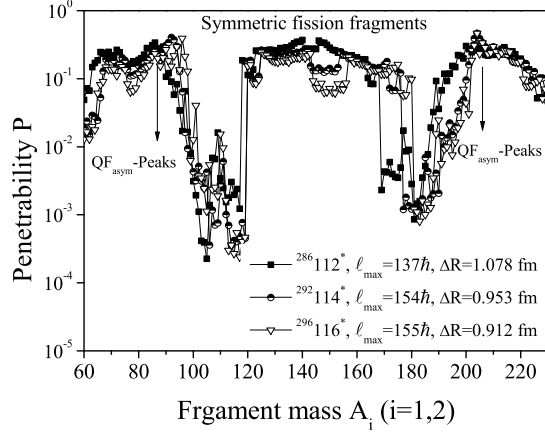


Figure 4.4: Variation of penetration probability with the fragment mass for the decay of $Z=112$, 114 , and 116 superheavy nuclei, by including the β_{2i} -deformation effects within hot optimum approach. Symmetric fission fragments can have fusion-fission and quasi-fission origin. The penetrability of asymmetric quasi-fission fragments are also shown.

of quasi-fission and fission processes increases. As compared to the decay of $^{286}112^*$, the asymmetric quasi-fission shows dominance (lower fragmentation potential) for $Z=114$ and 116 nuclei, and competes with the symmetric fission. This observation seems to suggest that quasi-fission component is higher for higher Z nuclei, synthesized at comparable incident energy.

Fig. 4.4 shows the penetration probability (P) of the decaying fragments of $Z=112$, 114 , and 116 superheavy nuclei. Comparable magnitude of penetration probability is observed for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei, at excitation energy ~ 39 MeV. Higher magnitude of penetration probability is observed for the symmetric ($FF+QF_{symmetric}$) as well as asymmetric region, supporting the results reported in Fig. 4.1 and Fig. 4.2 plotted for the fragmentation potential and preformation probability respectively. Hence, from the above discussion it is evident that the preformation and penetration probabilities are much higher for symmetric and asymmetric (quasi-fission) fragments. Note that in Fig. 4.1-4.4, the asymmetric quasi-fission peaks are shown at that value of ΔR which is fixed to address the FF process. It is so because we wanted to see the comparative emergence of QF-component along with the fission fragments. The calculated σ_{FF} and $\sigma_{QF_{asym}}$ are

SECTION 4.2: CALCULATIONS AND RESULTS

Table 4.1: The DCM calculated fusion-fission (σ_{FF}) and asymmetric quasi-fission (σ_{QFasym}) cross-sections for the decay of compound systems $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ formed in $^{48}\text{Ca}+^{238}\text{U}$, $^{48}\text{Ca}+^{244}\text{Pu}$, and $^{48}\text{Ca}+^{248}\text{Cm}$ reactions, respectively.

Z_{CN}	A_{CN}	E_{CN}^* (MeV)	T (MeV)	ℓ_{max} ($\hbar$)	ΔR (fm)	σ_{FF}^{DCM} (mb)	$\sigma_{FF}^{Expt.}$ (mb)	ΔR (fm)	σ_{QFasym}^{DCM} (mb)	$\sigma_{QFasym}^{Expt.}$ (mb)
112	286	39 $\pm$ 2	1.244	137	1.078	9.50	≤ 9.2	0.993	175.60	175.26
		35 $\pm$ 2	1.178	133	1.057	4.18	≤ 4.2	0.954	101.80	101.78
114	292	40 $\pm$ 2	1.246	154	0.953	6.06	≤ 6.0	0.801	86.20	86.15
		35 $\pm$ 2	1.167	150	0.942	2.28	≤ 2.2	0.743	44.60	44.75
116	296	39 $\pm$ 2	1.222	155	0.912	3.90	≤ 4.0	0.814	88.40	88.0
		32 $\pm$ 2	1.109	144	0.894	0.70	≤ 0.7	0.717	28.80	28.73

reported in Table 4.1 along with corresponding E_{CN}^* and ΔR . The calculated results are in decent agreement with the experimental data.

The experimental results of [5] show the measurements of the capture cross-section, which are estimated as : $\sigma_{FF} + \sigma_{QF}$ (neutron emission contribution is very less, in pb). Furthermore, the individual estimates of fusion-fission cross-sections are also given. In view of above experimental observations, where the separate contribution of σ_{FF} and $\sigma_{capture}$ [5] are reported, the DCM is applied to the same, using the β_{2i} -deformations within the optimum orientation approach. In this chapter, an attempt is made to address the individual σ_{FF} and σ_{QFasym} . The fragments chosen for the fusion-fission are marked in Fig. 4.2 (preformation plot). Reasonable agreement of cross-sections is obtained for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei within the limits of $A/2 \pm 20$ as shown in Table 4.1. Note that the upper estimates of the cross-sections are addressed using DCM framework around the barrier. Lower magnitude of ℓ_{max} and ΔR are required for below barrier dynamics, whereas relatively higher value of these parameters are employed to address the σ_{FF} at higher energies say ~ 39 MeV.

In addition to FF component, the symmetric QF may also appear due to the symmetric mass split. It may originate from the same mass region as the symmetric fragmentation is reinforced through the Sn-magicty. Although we could not single

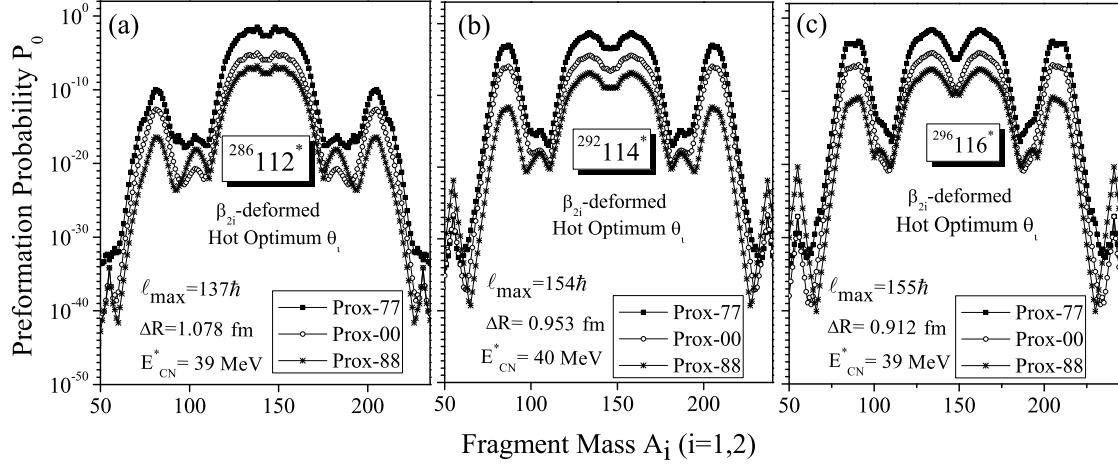


Figure 4.5: Preformation probability plotted with the fragment mass for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, and (c) $^{296}116^*$ superheavy nuclei within the application of different versions of proximity potentials, namely Prox-77, Prox-88, and Prox-00.

out the fragments contributing toward fission and symmetric QF, so the symmetric QF component is not explored explicitly in this work. However detailed analysis of asymmetric QF is worked out as discussed below. $\sigma_{QF_{asym}}$ are estimated by considering the the quasi-fission peaks lying around $A_1=208$, 210, and 211 ($Z_1 \sim 82$) respectively for $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei. The experimental value of $\sigma_{QF_{asym}}$ is obtained as the difference between capture cross-section and the cross-sections of symmetric fragments [5]. In the DCM framework, it is calculated by distributing $P_0=1$ only to these fragments i.e. the fragments shown in Fig. 4.2 around Pb peak and their complementary fragments. Nice fitting of experimental data of $\sigma_{QF_{asym}}$ is acquired in the DCM formalism, as shown in Table 4.1. The behavior of the neck-length parameter is same as that for the fusion-fission process i.e. lower magnitude is obtained for below barrier region and it increases with energy.

In order to extract the better picture of the decay paths of $Z=112$, 114, and 116 nuclei, Fig. 4.5 is plotted to check the effect of different proximity potentials on the preformation profiles of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ nuclei, studied at comparable incident energy, above the Coulomb barrier. This figure is plotted to see whether

the fission and quasi-fission region is modified, with the change in proximity part of the total fragmentation potential. Different proximity potentials, namely Prox-77, Prox-00, and Prox-88 are taken from references [17–19]. From the above figure it can be clearly seen that the position of asymmetric quasi-fission and fission peaks remains intact if we replace the Prox-77 potential with Prox-00 and Prox-88. The asymmetric quasi-fission peaks are obtained around lead (Pb) and its complementary fragments. Only the magnitude of the preformation probability is modified with the inclusion of different proximity potentials, the magnitude is higher for the Prox-77 and remains lowest for Prox-88. Note that the role of different proximity potentials is analyzed at the same neck-length parameters (as fixed for Prox-77), since the aim here is to address the structural distribution in the decay profile. From above discussion, one may conclude that the decay structure of superheavy nuclei $Z=112$, 114, and 116 is almost independent of the choice of proximity potential.

(ii) $\overline{TKE}$ -distribution of $Z=112$, 114, and 116 superheavy nuclei:

As mentioned earlier, TKE or $\overline{TKE}$ distribution of the fragments play extremely important role to apprehend the superheavy reaction dynamics. The TKE is taken as first turning point of penetration path in the scattering potential i.e. $TKE=V(R_a)$, as also calculated in the previous DCM based work to address the dynamics of $^{286}112^*$ nucleus across the barrier [12]. In the TKE analysis of $^{286}112^*$, Gaussian distribution of the decay fragments was observed, with higher magnitude as compared to the experimental TKE data. This might be due to the estimation of TKE distribution at ℓ_{max} . Note that in the calculation of rotational energy component, sticking moment of inertia is taken into account (mentioned in chapter 2), henceforth the magnitude of angular momentum reported in DCM based calculation is much higher. Probably, the higher magnitude of angular momentum is responsible for higher magnitude of TKE values. Similar results are obtained in the present work for average $\overline{TKE}$ -distribution of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei. Following [12], first the experimental $\overline{TKE}$ distribution is addressed by using Prox-

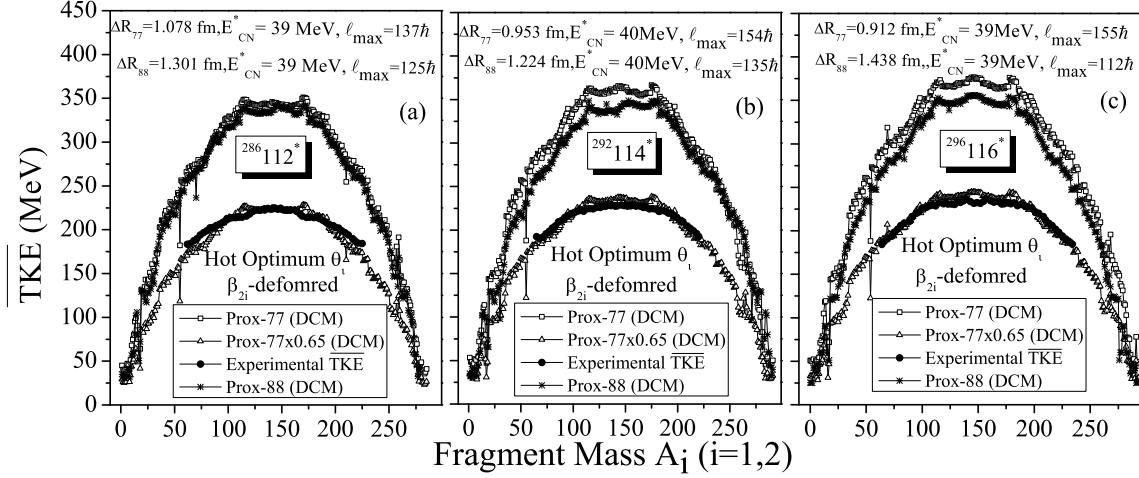


Figure 4.6: $\overline{TKE}$ - distribution of the fragments plotted for the decay of (a) $^{286}112^*$, (b) $^{292}114^*$, (c) $^{296}116^*$ superheavy nuclei, using hot optimum orientations and β_{2i} -deformations. The calculated $\overline{TKE}$ values are plotted for Prox-77, modified Prox-77 and Prox-88 values.

77 potential at ℓ_{max} , shown in Fig. 4.6 for $Z=112$, 114, and 116 superheavy nuclei. Using these parameters, the DCM calculated $\overline{TKE}$ is reported to be higher than the experimental values. The measured and calculated $\overline{TKE}$ -values have significant mismatch, irrespective of the mass the decaying nucleus. Specifically speaking, the difference is least for $^{286}112^*$ nucleus, which becomes relatively higher for $^{292}114^*$ and further for $^{296}116^*$ nucleus. For better comparison with $\overline{TKE}$ -values, the empirical factor of 0.65 is included in the Prox-77 approach, shown above in Fig. 4.5 and consequently the $\overline{TKE}$ -values are substantially reduced finding reasonable agreement with the experimental data. This factor is in agreement with the one reported to address the $\overline{TKE}$ distribution of the Lead (Pb) nucleus [21], which inturn seem to suggest that a fixed reduction factor takes care of the $\overline{TKE}$ distribution from heavy to superheavy mass region. As the DCM calculated $\overline{TKE}$ values are much higher than the experimental data, hence in the following work, an attempt is made to address this issue via (i) modifying the proximity part of the total potential, (ii) reduction in angular momentum component with the use of different versions of radii,

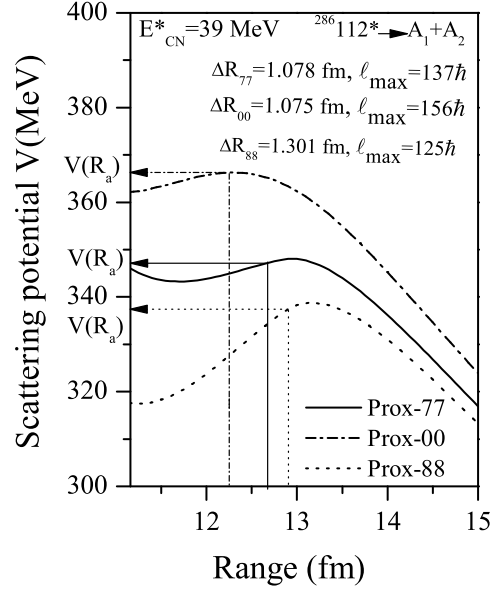


Figure 4.7: Scattering potential, plotted to observe the TKE (or $\overline{TKE}$)-values with the use of Prox-77, Prox-00 and Prox-88 potentials at the fixed neck-length parameter (ΔR) and maximum value of the angular momentum (ℓ_{max}).

mentioned in chapter 2.

Fig. 4.7 is plotted here to check the effect of different proximity potentials on the TKE and further on $\overline{TKE}$ -distribution of the decay fragments of $Z=112$, 114, and 116 nuclei. Precisely, this figure is plotted to calculate TKE value of the most symmetric fission fragments, so that an idea be extracted about the effect of different proximity potentials on $\overline{TKE}$ of the decaying fragments. Fig. 4.7 clearly shows that the potential calculated at the first turning of the penetration path, equivalent to TKE of the given fragment is modified with the application of different proximity approaches, namely Prox-77, Prox-88, and Prox-00. In view of Eq. (2.58), equivalent effect of proximity potential can be observed on average $\overline{TKE}$ -values. As the barrier characteristics are different for different proximity potentials, henceforth lowest barrier is obtained for the use of Prox-88 as compared to Prox-00 and Prox-77, observed at ℓ_{max} and at fixed ΔR . Due to lower barrier, the value of $V(R_a)$ hence TKE (or $\overline{TKE}$) is minimum for Prox-88. On the other hand, it remains maximum

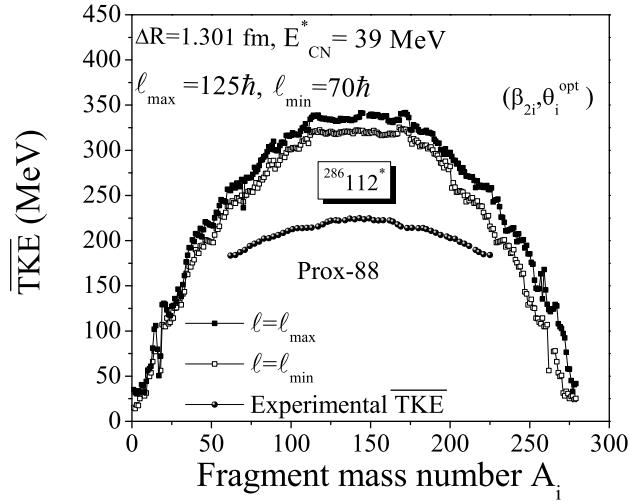


Figure 4.8: $\overline{TKE}$ -distribution of the $^{286}112^*$ fragments, plotted at extreme values of angular momentum i.e. ℓ_{max} and ℓ_{min} values for Prox-88 potential.

for Prox-00, whereas Prox-77 shows intermediate magnitude. Similar results were obtained in the previous work of DCM [22], applied for $^{48}\text{Ca} + ^{96}\text{Zr}$ reaction. As the potential exhibiting lower barrier are preferable to address TKE (or $\overline{TKE}$)-distribution, so the use of Prox-88 seems more justified for the decay analysis of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei. It is important to mention that Fig. 4.7 is plotted for $^{286}112^*$ nucleus and same conclusion can be withdrawn for $^{292}114^*$ and $^{296}116^*$ superheavy nuclei. In view of this figure, the $\overline{TKE}$ -distribution of the fragments for Prox-88 is also shown in the Fig. 4.6, where relatively smaller $\overline{TKE}$ -values are reported for the Prox-88 as compared to Prox-77. Hence Prox-88 can be chosen as a better option to understand the dynamics involved through the $\overline{TKE}$ -distribution of the decaying fragments. Note that Fig. 4.6 is not plotted for Prox-00, because Fig. 4.7 clearly shows higher $\overline{TKE}$ -values for this potential.

Within the use of Prox-88 potential, the angular momentum effects are tested on the $\overline{TKE}$ -distribution of the decay fragments. Fig. 4.8 is plotted at ℓ_{max} and ℓ_{min} for $Z=112$ system only. It may be noted that similar results are obtained for $Z=114$ and 116 nuclei as well but the same are not shown here (to avoid repetition). This figure clearly signifies that if the angular momentum effects are reduced, the decrement in

the $\overline{TKE}$ -values is observed. Broadly speaking, reduction in $\overline{TKE}$ -values is about ~ 20 -25 MeV at minimum value of the angular momentum (ℓ_{min}) as compared to the values obtained at ℓ_{max} . Hence it is clear from above discussion that $\overline{TKE}$ distribution finds relatively better comparison with data at lower ℓ -values. Note that ℓ_{min} is the value of the angular momentum at which the channel cross-sections and penetration probability start contributing [10], below ℓ_{min} , the channel cross-sections and penetrability attain negligible magnitude. In addition to the above discussion, it is important to note that the experimental $\overline{TKE}$ -distribution of the fragments are measured for HMF and fission region of decaying fragments, approximately from $A=60$ -225. However, in the DCM framework we can address the $\overline{TKE}$ -distribution of light particles and intermediate mass region (IMF) as well in addition to HMF and fission fragments.

From above discussion, one may conclude that the use of Prox-88 at lower ℓ -values can be considered as the better option to handle the $\overline{TKE}$ -distribution of the fragments. Although, the data is still overestimated by a significant factor which calls for further modification. One may realize the fact that as TKE ($\sim V(R_a)$) is the function of the radius of the emitting nuclei, hence the choice of the radius play eminent role to understand the dynamics involved through the TKE (or $\overline{TKE}$)-distribution of the decaying fragments. In view of this, different versions of radius are tested, given by Eqs. (2.6-2.11) in the Prox-88 potential. These observations are taken without considering the neck formation effects, i.e. $\Delta R=0$. It is relevant to mention that upto now, we have used the expression of radius given by Eq. (2.6), the dynamics involved through other versions of radii is tested in Fig. 4.9, in which $V(R_a) \sim$ TKE distribution is plotted for the most symmetric fission fragment. This figure reveals that the lowest value of the TKE is obtained for the use of Eq. (2.10) i.e. the radius used to address the CW 76 proximity potential, within the deformed fragmentation approach and hot optimum orientations. In addition to this, reduced values of TKE are also predicted for the use of radius given by Eq. (2.11). On the

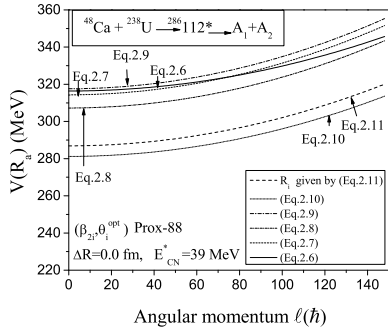


Figure 4.9: $V(R_a)$ or TKE values given for different radii used in the Prox-88 potential at $\Delta R=0$, plotted at minimum values of angular momentum.

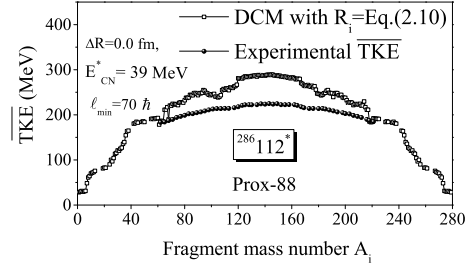


Figure 4.10: $\overline{TKE}$ -distribution of the fragments, plotted using Prox-88 potential at $\Delta R=0.0$ fm and at minimum value of angular momentum ℓ_{min} .

other hand reasonably high TKE values are observed for radii given in Eq. (2.7) to (2.9). Another observation from this figure confirms the result of Fig. 4.8, in which reduced $\overline{TKE}$ -values are reported at lower values of the angular momentum. For all the radii, the magnitude of TKE-values of the fragment increases with ℓ -values of the decay fragments. Hence one may conclude that the radius of decaying nuclei play important role in the TKE (or equivalently $\overline{TKE}$)-distribution of the fragments. It is important to mention that Fig. 4.9 is plotted for the decay of $Z=112$ nucleus, similar results are observed for $Z=114$ and $Z=116$ nuclei. Fig. 4.9 is plotted to extract the effect of different radii on the decay of most symmetric decay fragments, so that an idea may be developed to exhibit better description of the $\overline{TKE}$ -distribution.

Finally, Fig. 4.10 is plotted for the decay of $^{286}112^*$, superheavy nucleus at $\Delta R=0$ fm, minimum value of the angular momentum (ℓ_{min}) and with the radius approximation given by Eq. (2.10), using Prox-88 approach. Here $\Delta R=0$ fm is chosen because, with inclusion of neck-length parameter (ΔR) TKE contribution increases further. This is the best combination to address the $\overline{TKE}$ -distribution of the decay fragments. From Fig. 4.10, one may see that with the inclusion of the radius given by Eq. (2.10), the $\overline{TKE}$ values are further reduced by ~ 20 -25 MeV at $\ell_{min}=70\hbar$ for $^{286}112^*$ nucleus, and similar behavior is observed for $^{292}114^*$ and $^{296}116^*$

nuclei. In view of above discussion, one may conclude that within DCM approach, $\overline{KKE}$ -values are tested by modifying the different parameters of the model, but still the $\overline{KKE}$ -values are overestimated. It will be of further interest to explore the possible influence of quasi-fission component reported earlier on $\overline{KKE}$ -distribution profile.

In view of above, it is clear that to address the $\overline{KKE}$ -distribution of the fragments within DCM, an empirical factor of 0.65 is required. Beside this, Prox-88 provides better option with no neck criteria ($\Delta R=0$ fm) at lower values of angular momentum and appropriate choice of interaction radius. As the desired values of $\overline{KKE}$ are still not obtained, so this study needs further exploration in near future.

Since the distinction between FF and QF processes is an ongoing quest, so to generalize the results for whole superheavy mass region, the work is further extended by considering the ^{238}U -induced reactions. The fission and quasi-fission cross-sections are addressed for $Z=108, 112, 114$, and 120 superheavy nuclei. For the sake of consistency with the experimental observations [16], the fission cross-sections ($\frac{A}{2} \pm 20$) include the contribution from FF and symmetric QF components. The experimental fission cross-sections ($\frac{A}{2} \pm 20$) are extracted from Fig.6 (shown by circles) of Ref. [16] and compared with the DCM calculations. Along with this, the affects of deformations and orientations is studied for the better understanding about the origin of fission peaks. The detailed discussion about the same is carried out in the upcoming section.

4.2.2 Effect of optimum orientations on the fission dynamics of ^{238}U -induced reactions

Fig. 4.11 represents the preformation yield of ^{238}U -induced reactions formed via ^{36}S , ^{48}Ca , ^{48}Ti , and ^{64}Ni projectiles at energies near the Coulomb barrier. The preformation path is plotted for both hot and cold optimum orientations at best fitted neck-length parameters of hot compact approach. To avoid confusion in terminology,

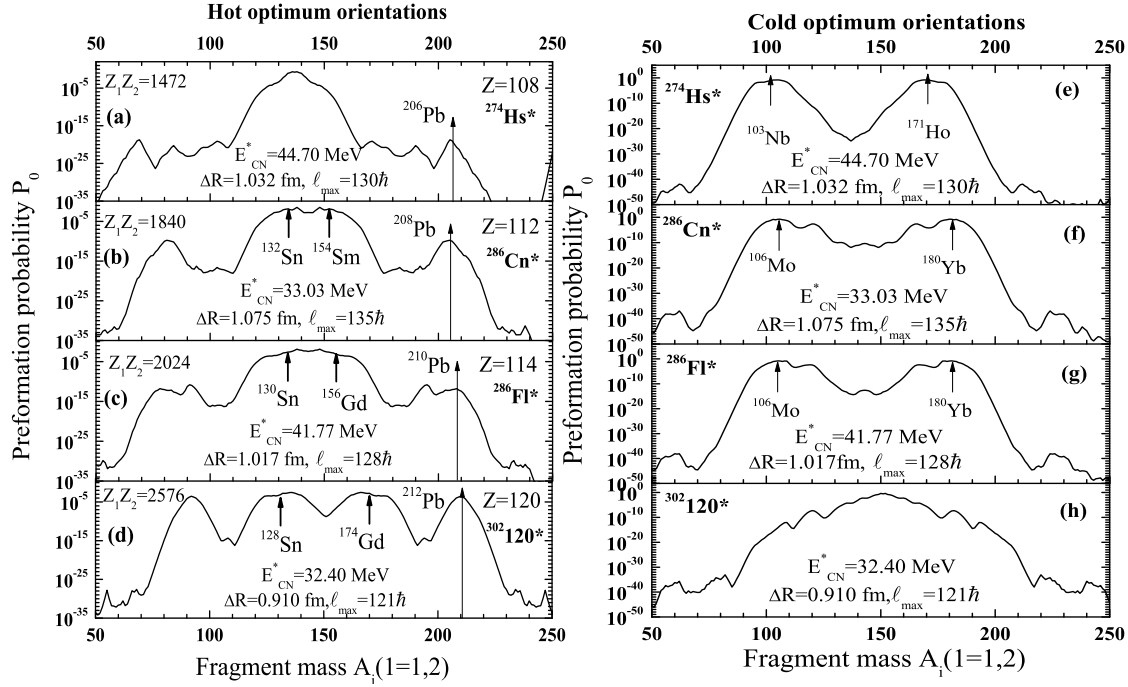


Figure 4.11: Left panel (hot orientations) and right panel (cold orientations) shows the preformation probability (P_0) as a function of fragment mass (A_i) plotted at near the Coulomb barrier energies for $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}120^*$ nuclei.

these are also referred as equatorial (side-side) and polar (tip-tip) configurations respectively. The left panel of Fig. 4.11 show that for hot orientation approach, symmetric distribution of fission fragments is observed for $^{274}\text{Hs}^*$ nucleus. As no other peaks are noticed in symmetric region, henceforth, the fission is considered as the main decay mode and the fragments in $\frac{A}{2} \pm 20$ region are used for the evaluation of fission cross-sections. With increasing charge number say for $^{286}\text{Cn}^*$ and $^{286}\text{Fl}^*$ nuclei, symmetric region ($\frac{A}{2} \pm 20$) starts broadening and some peaks appear near Sn region as shown in Fig. 4.11(b) and (c). These peaks are clearly visible for $^{302}120^*$ and hence highly asymmetric fragmentation is observed for the same as shown in Fig. 4.11(d). This indicates enhancement in the contribution of symmetric quasi-fission while shifting from $Z=108$ to $Z=120$ superheavy nucleus. In addition to symmetric fragmentation, the signature of asymmetric quasi-fission is also observed for the decay of above nuclei, as the peaks around Pb-magicity become prominent

SECTION 4.2: CALCULATIONS AND RESULTS

particularly for higher Z nuclei. Although some asymmetric peaks are obtained for $Z=108$ nucleus in Fig. 4.11(a), but the collective clusterization approach depicts that the contribution of QF_{asym} due to Pb-magicity is feeble as compare to symmetric fission region. Relatively symmetric preformation profiles are obtained for lower superheavy systems which becomes asymmetric when the extreme massive region of superheavy nuclei is explored. As the charge number of the nuclei increases from $Z=112$ to $Z=120$, enhancement in the asymmetric quasi-fission contribution is evidently large which is in line with the results obtained from ^{48}Ca -induced reactions. Conclusively, one can say that, with enhancement in Coulomb factor i.e. $Z_1Z_2=1472$ ($^{274}\text{Hs}^*$) to $Z_1Z_2=2576$ ($^{286}120^*$), the possibility of QF_{asym} increases. Furthermore, the average position of asymmetric quasi-fission peaks due to doubly magic Pb changes from 206u for $^{36}\text{S}+^{238}\text{U}\rightarrow^{274}\text{Hs}^*$ to 212u for $^{64}\text{Ni}+^{238}\text{U}\rightarrow^{302}120^*$ reaction.

Further, the role of cold orientations is also explored for the decay of considered nuclei. It was shown experimentally that for the equatorial interactions of two nuclei, there is a higher possibility of compound nucleus formation. However, quasi-fission events dominate in pole side interactions [4, 23, 24]. To confirm the same, calculations are conducted for cold orientation approach at same excitation energies as that in hot interaction, shown in the right panel of Fig. 4.11. The preformation yields of different nuclei for cold orientations are plotted at the best fitted neck-length parameters of hot orientations so that one may differentiate between the two. In contrast to hot orientation approach, within cold interactions highly asymmetric behavior is observed for $Z=108$ nucleus (Fig. 4.11(e)) which become symmetric in nature on going towards $Z=120$ system (Fig. 4.11(h)). However the origin of these asymmetric peaks in cold orientation approach is different from traditional Pb-valley. In the decay of $^{274}\text{Hs}^*$, asymmetric humps appear around ^{103}Nb (and ^{171}Ho) which are modified for $^{286}\text{Cn}^*$ and $^{286}\text{Fl}^*$ nuclei and observed across ^{106}Mo (and ^{180}Yb). No such peaks are visible for $^{302}120^*$ nucleus as only symmetric frag-

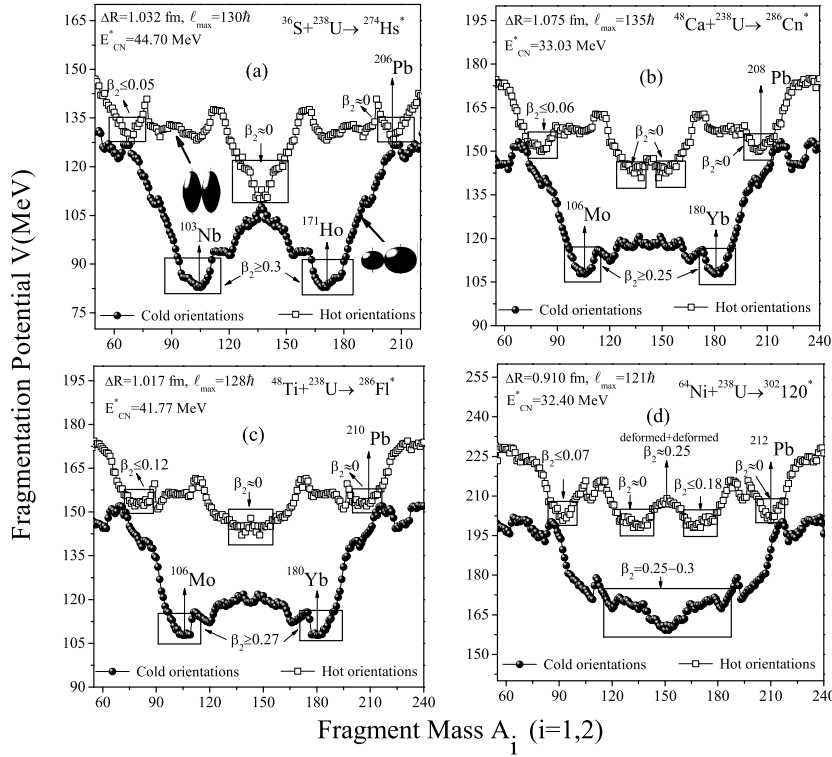


Figure 4.12: Fragmentation potential $V(\eta, R)$ plotted with fragment mass (A_i) for (a) $^{274}\text{Hs}^*$, (b) $^{286}\text{Cn}^*$, (c) $^{286}\text{Fl}^*$, and (d) $^{302}120^*$ nuclei formed via ^{238}U -induced reactions by considering hot and cold orientations of decaying fragments.

mentation is dominant. It means that in cold orientation approach fission follows different trajectory instead of usually reported Pb-peaks in hot interactions.

The opposite behavior of preformation yield of hot and cold orientations is related to the deformation and radius dependance of fragmentation potential (see Eq. (2.13)) which is plotted in Fig. 4.12 for the nuclei under consideration. One may find that for hot orientations (open square), the minima in fragmentation potential for all the studied cases are observed across the spherical or nearly spherical fragments, however for cold interactions (solid circles), the minima in potential are espied for highly deformed fragments. One interesting fact to be observed from Fig. 4.12(a) is that, in hot fragmentation profile of $^{274}\text{Hs}^*$, the fragments in $\frac{A}{2} \pm 20$ region have $\beta_2 \sim 0$ but on moving toward $^{302}120^*$, deformed fragments appear in symmetric region ($\frac{A}{2} \pm 20$) which inturn gives asymmetric distribution of preformation probability. It is due to the fact that in hot orientations the interactions between the

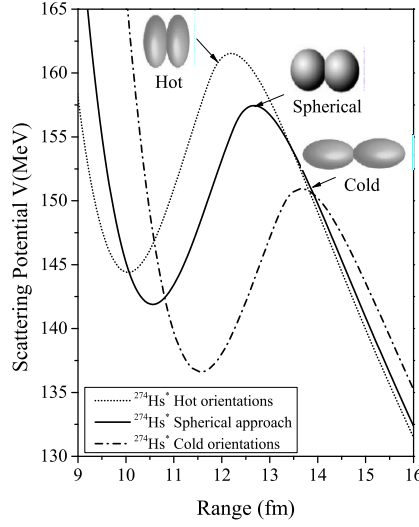


Figure 4.13: Variation of scattering potential as a function of range for spherical, cold, and hot interactions of the fragments.

spherical decaying fragments occurs at relatively larger distance as compare to the corresponding deformed nuclei (see Fig. 4.13). As a consequence of this the fragmentation potential of $^{274}\text{Hs}^*$ shows lower magnitude in $\frac{A}{2} \pm 20$ region and hence we get symmetric preformation yield as depicted in Fig. 4.11(a). Same argument is true for $^{286}\text{Cn}^*$ and $^{286}\text{Fl}^*$ superheavy nuclei (as shown in Fig. 4.11(b-c) and Fig. 4.12(b-c)). For $Z=120$ nucleus, a slight hump in the fragmentation potential of $\frac{A}{2} \pm 20$ region (Fig. 4.11(d)) is due to the appearance of deformed+deformed fragments ($\beta_2 \approx 0.25$) surrounded by spherical+weakly deformed fragments, thereby making preformation distribution more asymmetric (see Fig. 4.11(d)).

In contrast to above, opposite behavior is observed for the cold orientation approach as illustrated from Fig. 4.11(e-h) and Fig. 4.12(a-d). The spherical symmetric fragments ($\frac{A}{2} \pm 20$) having higher magnitude of preformation probability for hot optimum case (i.e. $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, and $^{286}\text{Fl}^*$) show significant suppression for the cold orientations of the fragments and peaks near highly deformed ^{103}Nb and ^{106}Mo ($\beta_2 \approx 0.30$ and 0.25 respectively) resulting in asymmetric behavior as shown in Fig. 4.11(e-g). The appearance of these peaks is due to the elongated interactions

of highly deformed fragments with larger radii which results in lower potential as compare to spherical nuclei (as shown in Fig. 4.13). Hence, lower fragmentation potential and enhanced P_0 is observed in heavy mass region (HMF) of $Z=108-114$ nuclei as illustrated in Fig. 4.12(a-c) and Fig. 4.11(e-g) respectively. For $^{302}120^*$ system highly deformed fragments appear in $\frac{A}{2} \pm 20$ region and its neighborhood within cold interaction criteria, and hence result in symmetric behavior of fragmentation. The effect of deformation and radius on the contribution of different constituent of potential is also explained in [25].

Table 4.2 illustrates the DCM calculated $\sigma_{\frac{A}{2} \pm 20}$ for $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}120^*$ nuclei. Along with this, other parameters like E_{CN}^* , $E_{c.m.}$, ΔR , ℓ_{max} etc are also tabulated. Table 4.2 shows that, using hot orientation criteria, the DCM calculated fission cross-sections find decent agreement with available experimental data [16]. However within cold approach, fission cross-section are underestimated for $Z=108, 112$, and 114 and overestimated for $Z=120$ superheavy systems due to the reverse trend of preformation behavior. Therefore, the use of cold orientations do not seems relevant for the addressal of experimental data of $Z=108-120$ nuclei (not shown in Table 4.2). Also the experimental yields [16] support the results of hot orientation approach and hence hot configurations are preferred for further calculations over cold one.

In addition to above, the present work is further extended to understand the mass distribution of nuclei on a broader scale and to check the contribution of different fission peaks (symmetric and asymmetric) toward cross-sections. For the purpose, $Z=104-120$ superheavy nuclei are taken which are formed via ^{238}U -induced reactions. Fig. 4.14 represents the preformation probability for considered nuclei at the Coulomb barrier energies for the hot orientation approach. It is depicted from Fig. 4.14 that the distribution of P_0 remain highly symmetric upto $Z=110$ i.e. $^{278}\text{Ds}^*$ (see Fig. 4.14(d)). Afterwards, more fragments start contributing toward fission and the sharp peaked preformation profile (for $Z=104-110$) gets broaden for

SECTION 4.2: CALCULATIONS AND RESULTS

Table 4.2: DCM calculated fission ($\sigma_{\frac{A}{2} \pm 20}$) cross-sections for $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, and $^{302}\text{120}^*$ nuclei using hot orientation approach and compared with experimentally available data of [16]. The excitation energies, temperature, neck-length parameters, and angular momentum values are also reported.

E_{CN}^*	$E_{c.m.}$	ΔR	ℓ_{max}	$\sigma_{\frac{A}{2} \pm 20}^{DCM}$	$\sigma_{\frac{A}{2} \pm 20}^{Exp.}$
(MeV)	(MeV)	(fm)	($\hbar$)	(mb)	(mb)
$^{36}\text{S} + ^{238}\text{U} \rightarrow ^{274}\text{Hs}^*$ ($V_C=159.1$ MeV)					
33.17	150.09	0.970	127	1.52	1.53
38.74	155.67	1.004	128	10.36	10.57
44.70	161.63	1.032	130	51.80	52.26
55.36	172.28	1.044	136	131.2	133.10
$^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}\text{Cn}^*$ ($V_C=193.8$ MeV)					
24.70	184.75	1.064	123	0.23	0.22
33.03	193.08	1.075	135	8.36	8.26
43.06	203.11	1.089	140	38.20	39.40
54.75	214.80	1.096	144	90.80	91.66
$^{48}\text{Ti} + ^{238}\text{U} \rightarrow ^{286}\text{Fl}^*$ ($V_C=214.7$ MeV)					
33.26	207.08	0.979	124	0.05	0.06
41.77	215.59	1.017	128	2.04	1.98
52.40	226.23	1.036	130	9.98	9.71
$^{64}\text{Ni} + ^{238}\text{U} \rightarrow ^{302}\text{120}^*$ ($V_C=266.4$ MeV)					
22.08	260.01	0.905	94	0.01	0.01
32.40	270.36	0.910	121	0.16	0.16
44.13	282.06	0.872	135	1.45	1.43
63.03	300.96	0.888	141	6.22	6.25

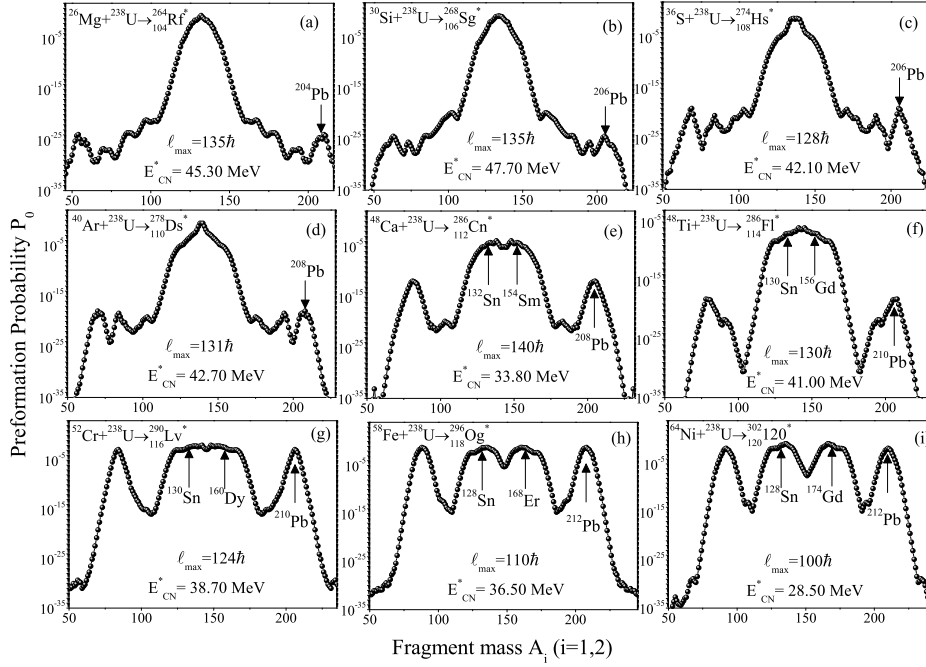


Figure 4.14: Variation of the preformation probability as a function of fragment mass for even nuclei (a) $^{264}\text{Rf}^*$ ($Z=104$), (b) $^{268}\text{Sg}^*$ ($Z=106$), (c) $^{274}\text{Hs}^*$ ($Z=108$), (d) $^{278}\text{Ds}^*$ ($Z=110$), (e) $^{286}\text{Cn}^*$ ($Z=112$), (f) $^{286}\text{Fl}^*$ ($Z=114$), (g) $^{290}\text{Lv}^*$ ($Z=116$), (h) $^{296}\text{Og}^*$ ($Z=118$), and (i) $^{302}120^*$ ($Z=120$). The figures are plotted at the excitation energies corresponding to the Coulomb barrier V_C .

$Z > 110$ nuclei with the appearance of some peaks around Tin (Sn) as shown in Fig. 4.14(e-i). These peaks suggest the possible involvement of symmetric quasi-fission events. Furthermore, the peaks near Pb (associated with the possible occurrence of asymmetric quasi-fission (QF_{Asym})) also start dominating and contribute significantly towards the total cross-sections. The yield of Pb-region is least for $^{264}\text{Rf}^*$ ($Z=104$) nucleus which starts increasing with increase in proton number. However, for heavier systems ($Z=116, 118$, and 120) the magnitude becomes comparable to symmetric region. The peaks are observed across different isotopes of Pb, as ^{204}Pb , ^{206}Pb appear for $Z \leq 108$ though for heavy systems ($Z > 108$), isotopes like ^{208}Pb , ^{210}Pb , and ^{212}Pb are perceived. Also, the peaks of symmetric quasi-fission (QF_{Sym}) are visible around different isotopes of Sn.

Finally, the fission ($\sigma_{\frac{A}{2} \pm 20}$) cross-sections are predicted for $Z=104-120$ nuclei using the DCM. The cross-sections are predicted at respective Coulomb barrier

SECTION 4.2: CALCULATIONS AND RESULTS

Table 4.3: DCM predicted fission ($\frac{A}{2} \pm 20$) cross-sections for nuclei $Z=104-120$, formed in ^{238}U -induced reactions at Coulomb barrier energies. The mass-asymmetry (η_A), compound nucleus formation probability (P_{CN}), E_{CN}^* , $E_{c.m.}$, and angular momentum are also reported. All the cross-sections are predicted by fixing the adjustable neck-length parameter $\Delta R=1.0$ fm.

Reaction	η_A	P_{CN}	$E_{c.m.}$ (MeV)	E_{CN}^* (MeV)	ℓ_{max} ($\hbar$)	$\sigma_{\frac{A}{2} \pm 20}^{DCM}$ (mb)
$^{26}\text{Mg} + ^{238}\text{U} \rightarrow ^{264}\text{Rf}^*$	0.803	0.486	122.30	45.30	135	64.80
$^{30}\text{Si} + ^{238}\text{U} \rightarrow ^{268}\text{Sg}^*$	0.776	0.420	141.50	47.70	135	70.40
$^{36}\text{S} + ^{238}\text{U} \rightarrow ^{274}\text{Hs}^*$	0.737	0.291	159.00	42.10	128	51.80
$^{40}\text{Ar} + ^{238}\text{U} \rightarrow ^{278}\text{Ds}^*$	0.712	0.0967	177.80	42.70	131	29.00
$^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}\text{Cn}^*$	0.664	0.0494	193.80	33.80	140	0.55
$^{48}\text{Ti} + ^{238}\text{U} \rightarrow ^{286}\text{Fl}^*$	0.664	0.00528	214.70	41.00	130	1.48
$^{52}\text{Cr} + ^{238}\text{U} \rightarrow ^{290}\text{Lv}^*$	0.641	0.00118	233.00	38.70	124	0.77
$^{58}\text{Fe} + ^{238}\text{U} \rightarrow ^{296}\text{Og}^*$	0.608	0.000424	249.70	36.50	110	0.23
$^{64}\text{Ni} + ^{238}\text{U} \rightarrow ^{302}\text{120}^*$	0.576	0.000146	266.40	28.50	100	0.87

energies by fixing $\Delta R=1.0$ fm. The value of ΔR is chosen because $\Delta R \sim 1.0$ fm is suitable to address the near barrier fission data (see Table 4.2) and hence $\sigma_{\frac{A}{2} \pm 20}$ are predicted at the same. The compound nucleus formation probability (P_{CN}) is also calculated using the relation given in Eq. (2.47). The values of P_{CN} along with other parameters like $E_{c.m.}$, mass-asymmetry (η_A) of entrance channel, E_{CN}^* , ℓ_{max} etc. are tabulated in Table 4.3. One can observe from Table 4.3 that with increase in charge and mass number of compound system, mass-asymmetry (η_A) decreases and hence P_{CN} also decreases due to the dominance of repulsive forces. As a result of this, the cross-sections are also influenced. The slight uncertainty in cross-sections can be observed because of the minor deviation of neck-length parameter from average value of $\Delta R \sim 1.0$ fm.

4.3 Conclusions

The FF and QF cross-sections are calculated for the decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei within the energy range of 32-40 MeV. The asymmetric quasi-fission is addressed via Pb magicity and the symmetric quasi-fission seems to find its origin in Sn region. The DCM calculated data matches well with the experimental findings. The indication of the quasi-fission process can also be governed through the capture stage. The $P_{CN} < 1$ suggest that the quasi-fission competes with the compound nuclear fission process. At above barrier energies, the comparative decay analysis of $Z=112$, 114 , and 116 is carried out in reference to fragmentation potential, preformation factor, and penetration probabilities. The impact of different proximity potentials is tested to address the structural distribution of decay profile of considered superheavy systems. Complementing this, the $\overline{TK\overline{E}}$ distribution is analyzed for considered superheavy nuclei. Here also the different versions of the proximity potentials are implied and Prox-88 seems to provide better option at lower angular momentum and $\Delta R=0$ consideration. Finally, the relative influence of a variety of nuclear radii is exercised in view of $\overline{TK\overline{E}}$ -distributions, emphasizing that choice of radius play equally important role.

Beside this, $\sigma_{\frac{A}{2} \pm 20}$ are addressed and compared with the available experimental data for ^{238}U -induced reactions leading to the synthesis of $Z=108$, 112 , 114 , and 120 superheavy nuclei. DCM calculated fission cross-sections find good agreement with the experimental data. The orientations (i.e. hot and cold) of nuclei with their symmetry axis relative to the decay directions are taken into account to explore the possibility of different decay mechanisms. For hot compact orientations of $Z=108$, 112 , and 114 nuclei, the symmetric mass yield is observed in addition to the contribution of asymmetric quasi-fission events which become highly asymmetric for cold orientations. But for $Z=120$ superheavy system opposite behavior is observed i.e. for hot criteria asymmetric fragmentation is noticed which become symmetric for cold orientations. The experimental mass yields support the hot orientations

over cold one and hence hot orientation approach is applied to study the structure analysis of $Z=104-120$ superheavy nuclei near Coulomb barrier energies. The mass distribution over a wide range suggest that symmetric distribution is observed for $Z=104-110$ nuclei with small contribution of asymmetric quasi-fission. Further, on moving towards heavier elements ($Z=120$), fragmentation become highly asymmetric which indicates higher possibility of quasi-fission components. The quasi-fission peaks are observed around neutron and proton shells closures at Pb and Sn. The position of asymmetric peaks shift across different isotopes of Pb on moving from $^{264}\text{Rf}^*$ to $^{302}120^*$ superheavy nuclei.

After analyzing fission dynamics of various even superheavy nuclei in this chapter, an effort is made to explore the dynamics of odd superheavy nuclei in the next chapter

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Chapter 5

Capture and fission analysis of various odd mass superheavy isotopes

Earlier chapters present the fission analysis of several even mass superheavy nuclei. This interpretation helps to develop the better understanding of considered superheavy isotopes. The present chapter is devoted to utilize this systematic for the exploration of peculiarities belonging to the odd mass nuclei. In the beginning of this chapter, the effect of temperature dependant deformations on the fission decay path of $Z=105$ superheavy nucleus is analyzed as the same is not incorporated in the previous study. Also, a comparative analysis of decay dynamics of $Z=105$ superheavy nucleus formed via different incoming channels is worked out. In extension to this, the fission excitation functions of even nuclei (available in whole superheavy mass range) is addresses within ℓ -summed Wong model to develop a hierarchy. As the experimental data related to fission processes of odd superheavy nuclei is not much reported in literature, so the available data is addressed in addition to some new predictions of fission excitation functions for $Z=107-111$ superheavy nuclei. For the purpose, numerous hot fusion reactions are taken into consideration and their relative contribution towards fission and quasi-fission events is also analyzed.

5.1 Introduction

The separation between the capture and fusion events is the main quest to handle the superheavy reaction dynamics. The origin of the nCN processes such as quasi-fission, quasi-elastic and deep-inelastic events, always hinder the superheavy compound nucleus formation [1,2], hence the fusion cross-sections generally have lower magnitude as compare to the capture cross-sections. The fusion of two colliding nuclei is a fundamental phenomenon, though there are various dynamical aspects which are not yet fully explored. The evolution of strenuous beam stream and delicate distinguishing methods have enabled to synthesize and study the nuclei in unexplored zone of nuclear chart. Numerous reactions and recognition strategies have been involved in the past to scrutinize transuranic elements. The most successful methods have been the fusion evaporation reactions of already known elements; recoil-separation techniques; identification through detectors *etc.* Such techniques are constantly refined further and employed for exploration of nuclear properties of new elements. The cold fusion reactions (^{208}Pb , ^{209}Bi + massive projectile ($A_P > 50$)) have been used since 1974 for the production of nuclei with $Z=107-112$ [3–5]. Woefully, the divination of cold fusion reactions are not sanguine because of increased fusion hindrance and small neutron excess. Within last two decades, researchers fortunately amalgamate six new SHE with $Z=113-118$ by following a different approach, in which high intensity beam of ^{48}Ca projectile is aimed at actinide targets [6–8]. Instead of this, the mass-asymmetric reactions of actinide nuclei with lighter projectiles like Magnesium (Mg) to potassium (K) are also of great interest to fill the gap between hot and cold fusion reactions.

Several experiments were performed for the cold synthesis of $Z=104-112$ superheavy nuclei like 104, 105, and 106 were synthesized in $^{208}\text{Pb}(^{48}\text{Ti}, 1n)^{255}\text{Rf}$, $^{208}\text{Pb}(^{50}\text{Ti}, 1n)^{257}\text{Rf}$ [9], $^{209}\text{Bi}(^{50}\text{Ti}, 1n)^{258}\text{Db}$, $^{208}\text{Pb}(^{51}\text{V}, 1n-2n)^{257-258}\text{Db}$ [10], and $^{208}\text{Pb}(^{52}\text{Cr}, 1n)^{259}\text{Sg}$ [11] respectively. The $Z=107$ superheavy system was produced in $^{209}\text{Bi}(^{54}\text{Cr}, 1n-2n)^{261-262}\text{Bh}$ and $^{208}\text{Pb}(^{55}\text{Mn}, 1n-$

$2n)^{261-262}\text{Bh}$ [12] reactions pairs and $^{208}\text{Pb}(^{58}\text{Fe},1n)^{265}\text{Hs}$ [13] report the synthesis of $Z=108$. Additionally, the pair reactions $^{209}\text{Bi}(^{58}\text{Fe},1n)^{266}\text{Mt}$ and $^{208}\text{Pb}(^{59}\text{Co},1n)^{266}\text{Mt}$ [14] were investigated for the production of $Z=109$. The experiments involving the synthesis of elements $Z=110$, 111, and 112 use respectively, $^{208}\text{Pb}(^{64}\text{Ni},1n)^{271}\text{Ds}$, $^{209}\text{Bi}(^{64}\text{Ni},1n)^{272}\text{Rg}$; $^{208}\text{Pb}(^{65}\text{Cu},1n)^{272}\text{Rg}$, and $^{208}\text{Pb}(^{70}\text{Zn},1n)^{277}\text{Cn}$ [15–17]. The enduring isotopes of SHE fabricated in the experiments are still neutron deficient. The short lifetime and low production cross-sections have posed difficulties in scrutinizing the various properties of superheavy elements. Therefore, the quest for suitable target-projectile combinations for the synthesis of stable superheavy elements is still going on. For the purpose, one can use the actinide targets with stable projectile lighter than ^{48}Ca to synthesize some unrevealed neutron deficient isotopes with high efficiency. Some of aforementioned elements were also synthesized using the reaction choices like, $^{248}\text{Cm}(^{19}\text{F}, xn)^{267-x}\text{Db}$; $^{249}\text{Bk}(^{18}\text{O}, xn)^{267-x}\text{Db}$ [18], $^{248}\text{Cm}(^{26}\text{Mg}, 5n-3n)^{269-271}\text{Hs}$ [19], and $^{238}\text{U}(^{36}\text{S}, 5n-3n)^{269-271}\text{Hs}$ [20]. The idea of using more asymmetric reaction pair reduces the suppression of fusion and hence results in higher compound nuclear formation cross-sections. The sensibility of colliding partners of a reaction guiding to the emergence of SHN play significant role even at near barrier energies. The synthesis cross-sections of these nuclei are very small. Hence, the rigorous computation and predictions of cross-sections are very crucial so that experimentalist be able to select the best target-projectile (t-p) combinations as well as required energy for the feasibility of superheavy synthesis.

Keeping this in mind, the fusion mechanism of $^{19}\text{F}+^{248}\text{Cm}\rightarrow^{267}\text{Db}^*$ and $^{18}\text{O}+^{249}\text{Bk}\rightarrow^{267}\text{Db}^*$ [18] reactions is analyzed using Wong model [21], where the barrier attributes such as barrier height (V_B), barrier position (R_B), and curvature ($\hbar\omega$) *etc* are estimated to have insight of reaction dynamics. Along with above reactions, the Uranium induced hot fusion reaction leading to $^{265}\text{Db}^*$ nucleus [22] is also investigated in the DCM framework [23–28]. Within this methodology, the symmet-

ric mass distribution of the fission fragments is governed through the hot-optimum configurations of the fragments, suggesting that FF is the prime decay mode for $^{265}\text{Db}^*$ and $^{267}\text{Db}^*$ nuclei. However, the endowment of the symmetric fission region gets significantly suppressed for the use of cold-elongated configurations of the fragments, subsequently giving rise to new fission valley with mass asymmetry $\eta=0.29$. Note that the compact configuration of the composite system is achieved usually at the energies higher than the Coulomb barrier, where the probability of head-on interaction is prominent. Conversely, elongated configuration of the nuclear system is perceived at the sub-barrier region exhibiting higher interaction radius and lower barrier height [29, 30]. However, in the present chapter, the interaction and decay analysis is observed near the Coulomb barrier, where both configurations may compete, and their barrier properties may help to distinguish between different decay events for $^{19}\text{F}+^{248}\text{Cm}$, $^{18}\text{O}+^{249}\text{Bk}$, and $^{27}\text{Al}+^{238}\text{U}$ reactions.

Furtherance, in this chapter, the main concern is on the coalescence of unknown superheavy isotopes with charge number $Z=107-111$. For the purpose, different actinide-based hot fusion reactions with light, medium, and heavy t-p combinations are considered. Firstly, the available experimental data is addressed for reliable predictions of capture (σ_{capture}) and fusion (σ_{fusion}) excitation functions. For light and medium nuclei, the fission barrier (B_f) is high and compound nucleus formation probability (P_{CN}) is close to unity i.e. $P_{CN} \approx 1$ and hence $\sigma_{\text{capture}} \approx \sigma_{\text{fusion}} \approx \sigma_{ER}$ [22, 31, 32]. But for heavy/superheavy systems, the scenario is different and nCN (or QF) processes and fusion-fission channels substantially determine the whole dynamics. The $P_{CN} < 1$ which leads to $\sigma_{\text{capture}} = \sigma_{\text{fusion}} + \sigma_{QF}$. Further, the contribution of evaporation residues (ER's) to fusion is very small (nb or pb order) and fusion-fission (ff) processes dominate, so $\sigma_{\text{fusion}} \approx \sigma_{ff}$ [33–35]. As the evaporation residue study of some isotopes of $Z=107-111$ is already done in [36] so the main interest here is: (i) to predict the capture and fusion-fission excitation functions for unknown superheavy nuclei with $Z=107-111$ in hot fusion reactions, (ii) competition between

quasi-fission and fusion-fission events is explored in terms of mass-asymmetry (η), Coulomb factor (Z_1Z_2), Businaro-Gallone mass-asymmetry point (α_{BG}) *etc*, (iii) determination of compound nucleus formation probability (P_{CN}), and (iv) influence of deformations and orientations on the fusion mechanism.

Chapter describe results and discussion in section 6.2 followed by conclusion in section 6.3.

5.2 Calculations and Results

The work carried out in the present chapter is based on the prescription given in chapter 2 and is fractionated into two subparts. In Section 5.2.1, the dynamics of $^{27}\text{Al}+^{238}\text{U}$ reaction leading to $^{265}\text{Db}^*$ [22] superheavy nucleus is examined, and fusion-fission (ff) cross-sections are estimated at near barrier energies. The fragmentation potentials and preformation probabilities are analyzed to address the fragmentation of ^{238}U -induced reaction and role of T-dependent deformations on the decay profile is explored. Following this, the evolution of $^{267}\text{Db}^*$ nuclear system formed in $^{19}\text{F}+^{248}\text{Cm}$ ($\eta=0.857$) and $^{18}\text{O}+^{249}\text{Bk}$ ($\eta=0.865$) [18] reactions is presented and an attempt is formulated to anticipated the capture and fusion-fission cross-sections. In Section 5.2.2, the ℓ -summed Wong model described in chapter 2 is applied to the analysis of experimental findings [2, 22, 29, 30, 37, 38] over a wide range of superheavy nuclei. A comparison of formation cross-sections for $Z=104-120$ superheavy elements and barrier characteristics is made at near and above barrier energies. Afterwards, the same methodology is used to evaluate the capture and fusion (or fusion-fission) excitation functions for $^{258,267,269,271}\text{Bh}$, $^{271,273,275}\text{Mt}$, $^{274,275,278,280}\text{Ds}$, and $^{275,277,279}\text{Rg}$ nuclei. The projectile and target combinations are chosen in such a way that their half lives are significantly large. As mentioned in the introduction, the contribution of σ_{ER} (of the order of nb and pb) toward fusion is very small as compare to the fusion-fission cross-sections (of the order of mb), which means that $\sigma_{fusion} \sim \sigma_{ff}$ and hence the fusion cross-sections (σ_{fusion}) estimated using Wong criteria are termed

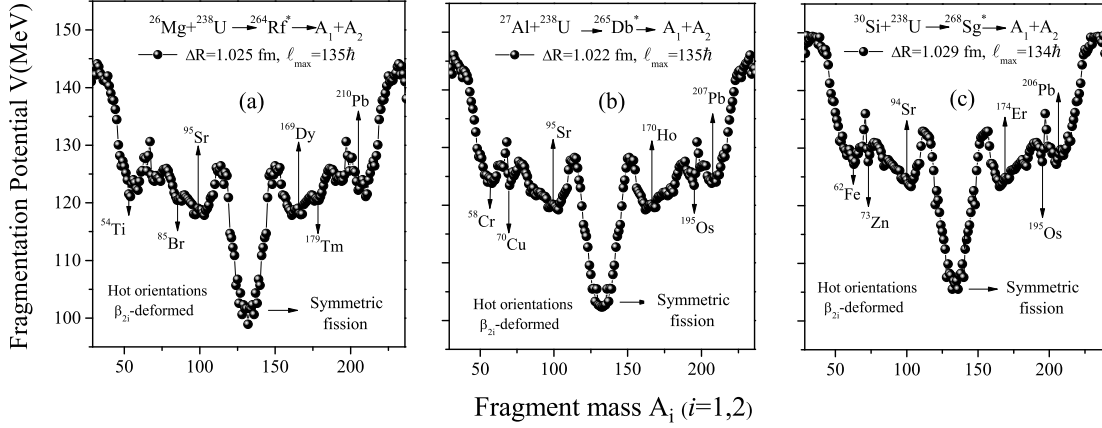


Figure 5.1: (a) Fragmentation potential $V(\eta, R)$ plotted with respect to fragment mass for the decay of (a) $^{264}\text{Rf}^*$, (b) $^{265}\text{Db}^*$, and (c) $^{268}\text{Sg}^*$ nuclei formed in the ^{238}U -induced reaction at fixed neck length parameter (ΔR) and angular momentum ($\ell_{\max}$) values, for static- β_{2i} deformed cases.

as fusion-fission cross-sections (σ_{ff}). Beside this, an attempt is made to analyze the different factors effecting the quasi-fission and fusion-fission contributions.

5.2.1 Dynamics of Db isotopes in ^{238}U , ^{248}Cm , and ^{249}Bk induced reactions

(i) The fission dynamics of $^{265}\text{Db}^*$ nucleus:

With the aim to inspect the dynamics of $^{27}\text{Al} + ^{238}\text{U} \rightarrow ^{265}\text{Db}^*$ reaction, the fragmentation potential for $^{265}\text{Db}^*$ nucleus is plotted in Fig. 5.1(b) by including β_{2i} -static deformations and hot optimum orientations. Fig. 5.1(b) is plotted for the wide mass range, in which symmetric mass division of the fission fragments is observed. Though some local minima's at ^{58}Cr , ^{70}Cu , and ^{95}Sr nuclei are observed, along with their complementary ($A_1 = A - A_2$) fragments, but the dominance of the symmetric fragmentation depicts that symmetric fission is the main contributor in the dynamics of $^{265}\text{Db}^*$ nucleus, when hot-compact deformed fragmentation is employed. Fig. 5.1(a) and Fig. 5.1(c) are also plotted here to observe the fragmentation behavior of

the neighboring $^{264}\text{Rf}^*$ and $^{268}\text{Sg}^*$ nuclei, so that a relative examination be achieved to address the decay of light superheavy mass nuclei. Note that the fragmentation potentials are plotted at energies around the Coulomb barrier. The decay of $^{268}\text{Sg}^*$ nucleus at $E_{c.m.}=144$ MeV was studied in the previous work [26], but Fig. 5.1(c) is plotted here to compare its fragmentation structure with $^{264}\text{Rf}^*$ and $^{265}\text{Db}^*$ nuclei, as mentioned above. Similar results are observed from Figs. 5.1(a) and (c), favoring symmetric mass fragmentation as the dominant decay channels. Hence one may conclude that for the light superheavy mass region, symmetric distribution of fragmentation is preferred for the hot compact orientations, which becomes highly asymmetric for the heavier superheavy nuclei such as $Z=115$ and 117 [25] and also discussed in the previous chapter. The magnitude of ΔR and ℓ_{max} remains almost constant for the decay of these nuclei. Note that the decay fragments may vary while going from $Z=104$ to $Z=106$, such as ^{54}Ti , ^{58}Cr , and ^{62}Fe fragments appear at first valley respectively for $^{264}\text{Rf}^*$, $^{265}\text{Db}^*$, and $^{268}\text{Sg}^*$ nuclei. In concurrence to this, different isotopes of lead (Pb) (and their complementary fragments) are also mentioned in Fig. 5.1, which may be associated to the possible occurrence of QF process.

In the present analysis, mainly two set of orientation approaches are employed in Figs. 5.2(a,b) and Fig. 5.2(c), respectively termed as hot and cold configurations. The hot orientations of the fragments lead to compact structures with lowest radius and higher barrier. On the other hand, elongated configurations with lower barrier and higher radius are perceived for the cold-oriented nuclei. In Fig. 5.2(a), we started with the preformation probability (P_0), plotted for the static deformed and hot-orientations of the fragments. The result of this figure may be correlated with the one plotted in Fig. 5.1(b) for fragmentation potential. In this figure, the decay of $^{265}\text{Db}^*$ compound nucleus clearly shows the symmetric mass division of the fission fragments, as analyzed in Fig. 5.1(b). The appearance of Pb-peaks in the decay path is generally associated with the phenomenon of the quasi-fission, but here

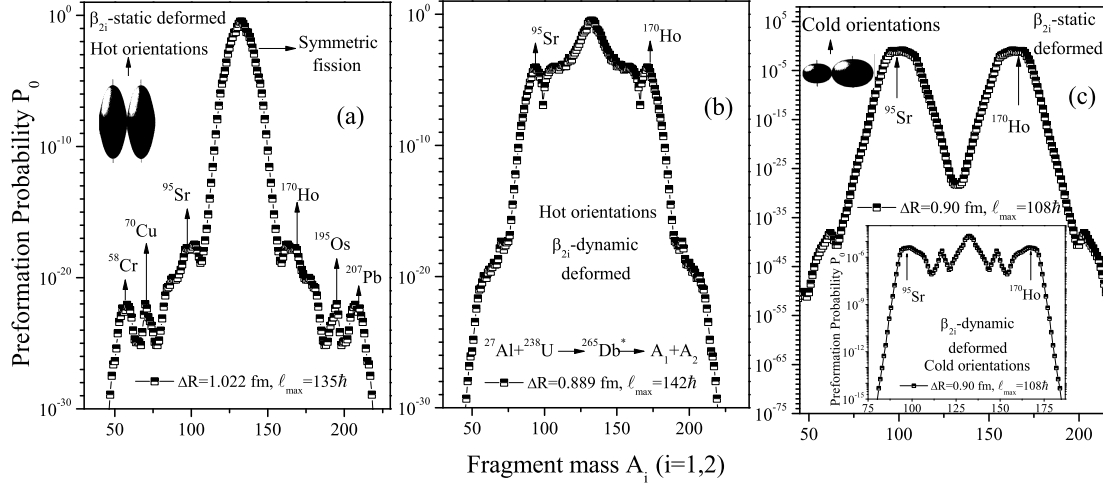


Figure 5.2: Preformation probability (P_0), plotted as a function of fragment mass for the decay of $^{265}\text{Db}^*$ nucleus using (a) hot static-deformed, (b) hot dynamic-deformed, and (c) cold static-deformed approaches. The figures are useful to extract the knowledge about different decay mechanisms and further used to calculate the fusion-fission cross-sections. The inset of Fig. 5.2(c) is same as that of the remaining figures, but plotted for the cold dynamic deformations of the nuclei.

the contribution of Pb-valley is quite small as the preformation probability for this region is negligible as compared to the symmetric fragments (see Fig. 5.2(a)). Similarly, the preformation probability for ^{95}Sr and its complementary fragment ^{170}Ho is larger than Pb-valley but still negligibly small as compared to the preformation factor for the fission region of $^{265}\text{Db}^*$ nucleus. Hence the decay of $^{265}\text{Db}^*$ nucleus is mainly characterized by the fusion-fission process while including static hot-compact orientations of the decay fragments.

In Fig. 5.2(b) the decay structure is significantly modified with the involvement of dynamical (T-dependent) β_2 -deformations (see Eq. (2.5) of chapter 2) within hot orientation approach for $^{265}\text{Db}^*$ nucleus. More fragments start contributing and relatively broader peak is observed for the fission fragments with $\frac{A}{2} \pm 25$, which otherwise remains $\frac{A}{2} \pm 15$ for the previous case (static β_2 -deformations). Broadly speaking, the symmetric yield starts broadening when the static β_2 -deformations

SECTION 5.2: CALCULATIONS AND RESULTS

are replaced by dynamic β_2 -deformations in the fragmentation analysis. Interestingly, the peaks around ^{95}Sr and ^{170}Ho , having negligible contribution as depicted in Fig. 5.2(a), start contributing significantly towards fission cross-sections when dynamical hot-fragmentation approach is applied. It is important to illustrate that majority of the minimized fragments near ^{95}Sr and ^{170}Ho peaks, ranging $A_2=85-110$ (and the complementary nuclei) are prolate-deformed. The interaction of prolate-prolate nuclei leads to the compact shape at minimum possible magnitude of the $R(\text{fm})$. At this $R(\text{fm})$, the Coulomb, proximity, and centrifugal or rotational potentials are calculated as shown in Figs. 5.3(a),(b), and (c) respectively for $A_2=85-110$ fragments. It may be noticed that, the Coulomb and centrifugal/rotational potentials vary inversely with $R(\text{fm})$, given by Eq. (2.20) and Eq. (2.21) respectively. However, the proximity part of the total potential has direct dependance on the radius i.e. $V_P \propto R$. The comparison of Fig. 5.2(a) and Fig. 5.2(b) can be carried out by arguing the fact that $R(\text{fm})$, which is fixed for the static deformed choice, starts increasing for the dynamic case as the deformations start diminishing with temperature. With increase in the radius parameters, given by Eq. (2.4) in chapter 2, the V_C and V_ℓ starts decreasing, as shown in Fig. 5.3(a) and Fig. 5.3(c) respectively. However Fig. 5.3(b) shows that V_P increases in the magnitude relative to the static deformed case. The decrease in the magnitude of V_C and V_ℓ is relatively larger and compensate the increased magnitude of the proximity potential. Hence the overall fragmentation ($V_C+V_P+V_\ell+B.E$) of $A_2=85-110$ nuclei decreases, and the preformation factor shows increment for the hot dynamic deformation of the nuclei, which otherwise shows lower preformation factor for static deformed case.

Purely asymmetric distribution of fragments is observed in Fig. 5.2(c) when the calculations are done using static cold-orientations. The preformation yield of the symmetric fragments $\frac{A}{2} \pm 15$ reduces significantly for cold-orientated nuclei, which otherwise show dominance in Fig. 5.2(a), plotted for the static hot-orientations of the decaying fragments. The contribution of the asymmetric cold oriented fragments

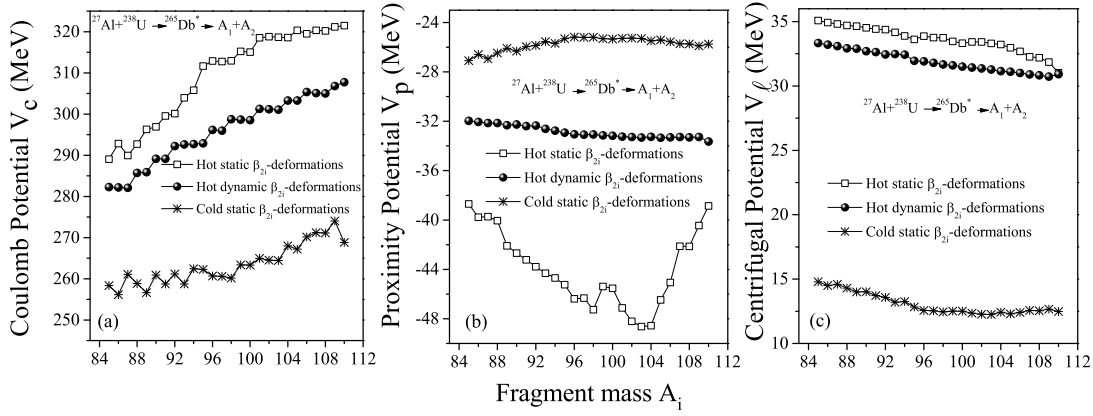


Figure 5.3: Variation of the (a) Coulomb (V_C), (b) proximity (V_P , Prox-1977), and (c) centrifugal (V_ℓ) potentials for the fragments lying in range $A_2=85-110$, by including the static and dynamic hot deformed configurations, along with static-cold orientations of the decay fragments.

corresponds the fission peaks with mass asymmetry $\eta=(A_H-A_L)/(A_H+A_L)=0.29$. Such fission region is also observed in the decay of $^{268}\text{Sg}^*$ nucleus [29, 30], which follows the decay trajectory near $\eta=0.33$. Note that, usually two fission trajectories are followed by the superheavy composite systems, one near the symmetric fission region with $\eta=0$ (fusion-fission) and other drags the formed nucleus towards the Pb-region with $\eta\sim 0.4$, sometimes associated with the asymmetric quasi-fission process. The signatures of symmetric quasi-fission can also be observed around Sn-region [28]. For the decay of $^{265}\text{Db}^*$ nucleus, the potential energy surface (PES), plotted as Fig. 5.2(c), show that the fission channel leading to Pb-region diminishes but a new fission channel with mass asymmetry $\eta=0.29$ opens up, possibly because of the deformation and orientation effects of decaying fragments. The prominent peaks in the mass distribution of $^{265}\text{Db}^*$ can be explained further through the contribution of V_C , V_P , and V_ℓ from Fig. 5.3 plotted at relatively larger radius, for the cold orientation approach. The implications of the cold optimum orientation favors interaction of nuclei at further higher values of the radius parameter $R(\text{fm})$, as shown pictorially in Fig. 5.2(c). For such configuration, the proximity potential is further enhanced with

respect to the dynamic hot deformed approach, to the significant extent, as depicted in Fig. 5.3(b). In addition to this, the Coulomb and centrifugal potentials decrease significantly, which drag the fragmentation potential to lower magnitude, eventually resulting in higher preformation yield for asymmetric fragments (around ^{95}Sr and ^{170}Ho nuclei). The role of dynamic deformations is also explored for cold deformed approach and the preformation yield for the same is shown in the inset of Fig. 5.2(c). With the inclusion of cold-dynamic deformations, the preformation structure gets modified. Although the peaks around ^{95}Sr and ^{170}Ho fragments remain intact with slight modification in magnitude but the symmetric region starts contributing which is suppressed in cold static case. Conclusively, the origin of the symmetric mass split occurs for all the mentioned cases except for the cold-static configurations of the fragments, where the dominance of the fragments around ^{95}Sr and ^{170}Ho nuclei seems evident. Hence from above discussion, one may conclude that the mass distribution of the fragments is highly dependent on the deformations and orientations of the decay fragments, which is symmetric for hot fragmentation approach and becomes asymmetric for cold orientations of the fragments.

(ii) Predictions of fission cross-sections for $^{267}\text{Db}^*$ nucleus:

In the recent analysis [18], experiment was performed for $Z=105$ nucleus by using different actinide targets such as ^{248}Cm and ^{249}Bk , and the neutron evaporation residue cross-sections were estimated. The same is addressed using DCM in chapter 3 and the role of I_S and I_{NS} moments of inertia is analyzed in reference to the $4n$ and $5n$ decay cross-sections of $^{267}\text{Db}^*$ nucleus. In this chapter, the comprehensive dynamics of $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions is worked out in terms of capture and fusion of the interacting nuclei. Note that the fission events for $^{265}\text{Db}^*$ nucleus are experimentally measured [22] which are addressed through the DCM framework in the preceding section. However, the fission measurements for $^{267}\text{Db}^*$ are not experimentally reported, hence the Wong calculated fusion cross-sections are first addressed, so that the $\sigma_{fission}$ be estimated, as σ_{fusion} and $\sigma_{fission}$ are related by the

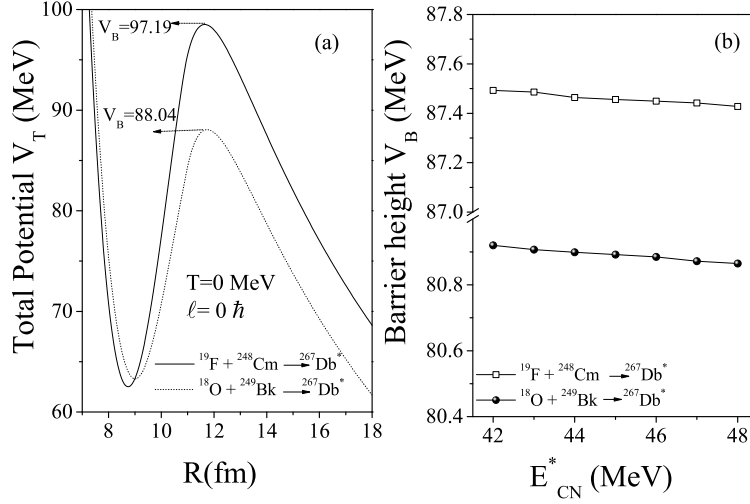


Figure 5.4: (a) Total interaction potential (V_T) as a function of range (R) for $^{267}\text{Db}^*$ nuclear system formed via two incoming channels *i.e.* $^{19}\text{F} + ^{248}\text{Cm}$ and $^{18}\text{O} + ^{249}\text{Bk}$. (b) Barrier heights (V_B) plotted for the above reactions at different excitation energies (E_{CN}^*).

relation $\sigma_{fusion} = \sigma_{fission} + \sigma_{EVR}$.

Following the above discussion, the scattering potential is plotted in Fig. 5.4 and the barrier characteristics V_B , R_B , and $\hbar\omega$ are extracted. The barrier characteristics have significant influence on the interaction cross-sections of nuclei, as a small change in the Coulomb barrier and distance between colliding nuclei influence the balance among attractive and repulsive forces. Fig. 5.4(a) is plotted to show the barrier characteristics of $^{267}\text{Db}^*$ nuclear system, in which Coulomb barrier and fusion pockets are depicted for $^{18}\text{O} + ^{249}\text{Bk}$ ($\eta=0.865$) and $^{19}\text{F} + ^{248}\text{Cm}$ ($\eta=0.857$) reactions. Additionally, the variation of barrier height with energy for above reactions is plotted in Fig. 5.4(b) for having better idea of barrier characteristics with E_{CN}^* . Lesser barrier height is depicted for the reaction having larger mass asymmetry ($\eta=0.865$) as the Coulomb factor $Z_1 * Z_2 = 776$ is relatively lower for ^{249}Bk induced reaction compared to $Z_1 * Z_2 = 864$ for $^{19}\text{F} + ^{248}\text{Cm}$ reaction. This indicates larger fusion probability for $^{18}\text{O} + ^{249}\text{Bk}$ reaction, leading to higher fusion cross-sections. Similar results are depicted from Fig. 5.4(b), indicating lower barrier height for $^{18}\text{O} + ^{249}\text{Bk}$

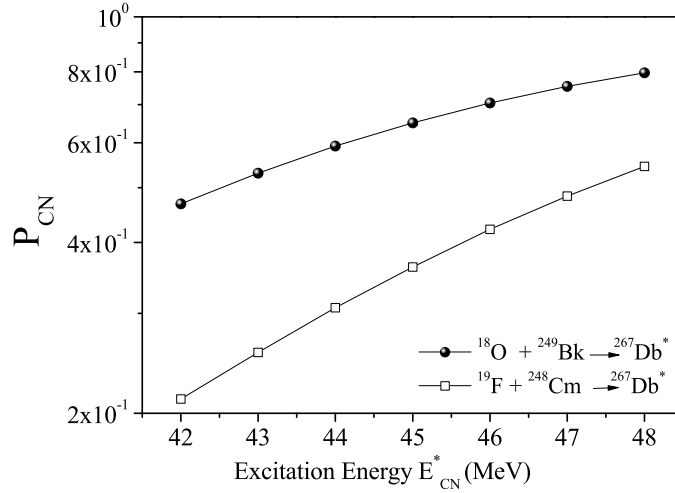


Figure 5.5: Compound nucleus formation probability (P_{CN}) of $^{267}\text{Db}^*$ nucleus produced via $^{18}\text{O} + ^{249}\text{Bk}$ and $^{19}\text{F} + ^{248}\text{Cm}$ reactions with E_{CN}^* .

reaction over wide energy range. The barrier height (V_B) is slightly modified with increase in energy across the barrier.

Beside barrier characteristics, the compound nucleus formation probability (P_{CN}) is equally important parameter to address the fusion possibility of the interacting nuclei. As evident from [39], the P_{CN} can be calculated as the ratio of FF and capture cross-sections. The uncertainties in the measurements of capture cross-sections are higher for superheavy region because the separation of elastic and quasi-elastic processes is difficult from the capture events. Also the contribution of quasi-fission process is often unknown. To avoid such uncertainties, the value of P_{CN}^0 is estimated in reference to [40]. In addition to this, the energy dependent P_{CN} is estimated using Eq. (2.47), and the same are plotted in Fig. 5.5 for $^{19}\text{F} + ^{248}\text{Cm}$ and $^{18}\text{O} + ^{249}\text{Bk}$ reactions. The energy range chosen for the calculation of P_{CN} is across the Coulomb barrier. From this figure it is clearly evident that P_{CN} for $^{267}\text{Db}^*$ is larger for relatively asymmetric reaction $^{18}\text{O} + ^{249}\text{Bk}$, and it varies from 0.468 to 0.797. However, for $^{19}\text{F} + ^{248}\text{Cm}$ reaction the magnitude of P_{CN} lies in the range 0.212 to 0.545. This confirms that the fusion probability is much higher

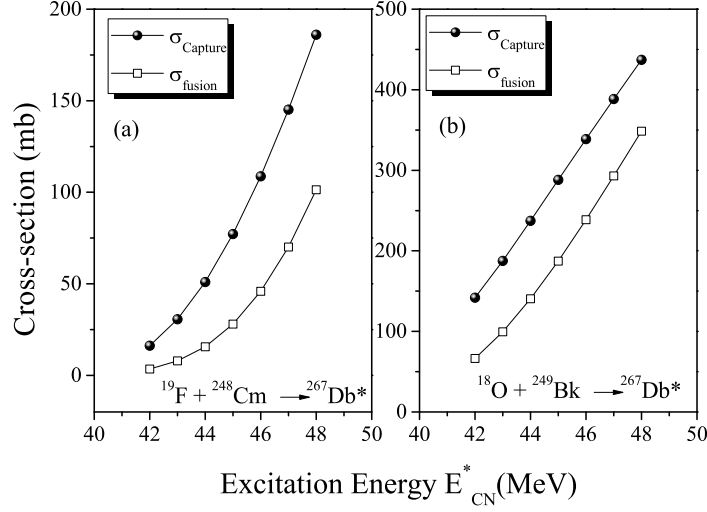


Figure 5.6: The Wong predicted capture and fusion cross-sections, for the reactions (a) $^{19}\text{F} + ^{248}\text{Cm}$ and (b) $^{18}\text{O} + ^{249}\text{Bk}$ leading to $^{267}\text{Db}^*$ nuclear system at energies near the Coulomb barrier.

for $^{18}\text{O} + ^{249}\text{Bk}$ interacting pair as compared to $^{19}\text{F} + ^{248}\text{Cm}$ reaction. Further, the compound nucleus formation probability show increment with energy for both the reactions, suggesting that the nCN process is more dominant in the sub-barrier region.

Fig. 5.6 shows the calculated capture and fusion cross-sections for $^{267}\text{Db}^*$ nucleus formed in $^{19}\text{F} + ^{248}\text{Cm}$ and $^{18}\text{O} + ^{249}\text{Bk}$ reactions. As the Wong model works nicely near and above the Coulomb barrier, hence the cross-sections are calculated for the near barrier energy range $E_{CN}^* = 42\text{--}48$ MeV. The figure clearly shows higher capture cross-sections than fusion for both reactions, indicating the occurrence of nCN processes in the formation of $^{267}\text{Db}^*$ nucleus. The chances of the nCN processes such as QF (symmetric or asymmetric) are relatively higher for $^{19}\text{F} + ^{248}\text{Cm}$ reaction due to lesser compound nucleus formation probability (P_{CN}) (see Fig. 5.5) and cross-sections (see Fig. 5.6(a)) for this reaction. Conversely, the P_{CN} for $^{18}\text{O} + ^{249}\text{Bk}$ interacting pair is quite high, leading to higher fusion cross-sections. Hence the fusion-dynamics is nicely elaborated using Wong methodology, and the same is subsequently analyzed within DCM, by assuming that $\sigma_{\text{fusion}} = \sigma_{\text{fission}} + \sigma_{\text{EVR}}$. The

SECTION 5.2: CALCULATIONS AND RESULTS

Table 5.1: DCM fitted fusion-fission cross-sections (σ_{ff}) of $^{265}\text{Db}^*$ and $^{267}\text{Db}^*$ nuclei formed respectively in $^{27}\text{Al}+^{238}\text{U}$ and ($^{19}\text{F}+^{248}\text{Cm}$, $^{18}\text{O}+^{249}\text{Bk}$) reactions by using hot compact configurations. The experimental and theoretical predicted (using Wong model) fusion-fission and capture cross-sections are also shown in Table. The contribution of fusion-fission cross-sections to the capture cross-sections are also tabulated in percentage form.

E_{CN}^* (MeV)	T (MeV)	ΔR (fm)	σ_{DCM}^{ff} (mb)	ℓ_{max} ($\hbar$)	$\sigma_{Exp.}^{ff}$ (mb)	σ_{Wong}^{ff} (mb)	$\sigma_{Exp.}^{Cap.}$ (mb)	$\sigma_{Wong}^{Cap.}$ (mb)	σ_{ff}/σ_{Cap} (%)
$^{27}\text{Al}+^{238}\text{U} \rightarrow ^{265}\text{Db}^*$									
49.5	1.45	1.022	83.40	135	85 ± 30	-	160 ± 25	-	53.1%
61.5	1.62	1.040	156.40	140	155 ± 50	-	330 ± 20	-	46.9%
$^{19}\text{F}+^{248}\text{Cm} \rightarrow ^{267}\text{Db}^*$									
42.0	1.34	0.978	3.50	114	-	3.43	-	16.17	21.2%
47.0	1.41	1.021	68.20	134	-	70.11	-	145.17	48.3%
$^{18}\text{O}+^{249}\text{Bk} \rightarrow ^{267}\text{Db}^*$									
42.0	1.34	1.038	65.80	127	-	66.35	-	141.78	46.8%
47.0	1.41	1.059	292.00	135	-	292.94	-	388.51	75.4%

contribution of the fission fragments for $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions come mainly through the symmetric mass distribution lying in the range $\frac{A}{2} \pm 15$, same as observed for $^{27}\text{Al}+^{238}\text{U}$ reaction [22]. The mass distribution of the fragments for $^{267}\text{Db}^*$ nucleus, formed in $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions is not shown here to avoid repetition. On the other hand, the contribution of the evaporation residues is feeble towards the total fusion cross-sections, as they are measured in the nb-range [18]. Following the above discussion on the fission processes, DCM and Wong fitted cross-sections are tabulated in Table 5.1 for ^{238}U , ^{248}Cm and ^{249}Bk induced reactions. The data in Table 5.1 is estimated at near barrier energies, along with the magnitude of the neck-length parameters.

5.2.2 Production of Z=107-111 superheavy nuclei via hot fusion reactions

The fission study of odd nuclei is further extended for Z=107-111 superheavy nuclei. First of all the available experimental data of fission is addressed within the ℓ -summed Wong model, to set a hierarchy which is further utilized to make some

predictions for Z=107-111 superheavy nuclei. The details of calculations is as given below.

(i) Comparison of barrier characteristics and cross-sections with available data:

Fig. 5.7 shows the capture and fusion (equivalently fusion-fission) excitation functions of superheavy nuclei with Z=104-120 at near and above barrier energies. The experimentally available capture (σ_{Cap}) and fusion-fission (σ_{ff}) cross-sections are compared with the theoretical estimates of ℓ -sum Wong model. For the purpose, $^{26}\text{Mg}+^{238}\text{U}\rightarrow^{264}\text{Rf}^*$ [22], $^{27}\text{Al}+^{238}\text{U}\rightarrow^{265}\text{Db}^*$ [22], $^{30}\text{Si}+^{238}\text{U}\rightarrow^{268}\text{Sg}^*$ [30], $^{34}\text{S}+^{238}\text{U}\rightarrow^{272}\text{Hs}^*$ [29], $^{36}\text{S}+^{238}\text{U}\rightarrow^{274}\text{Hs}^*$ [2], $^{35}\text{Cl}+^{238}\text{U}\rightarrow^{273}\text{Mt}^*$ [22], $^{48}\text{Ca}+^{238}\text{U}\rightarrow^{286}\text{Cn}^*$ [37], $^{48}\text{Ti}+^{238}\text{U}\rightarrow^{286}\text{Fl}^*$ [38], $^{48}\text{Ca}+^{244}\text{Pu}\rightarrow^{292}\text{Fl}^*$ [37], $^{48}\text{Ca}+^{248}\text{Cm}\rightarrow^{296}\text{Lv}^*$ [37], and $^{64}\text{Ni}+^{238}\text{U}\rightarrow^{302}120^*$ [38] reactions are taken into account and variation of cross-sections with excitation energy (E_{CN}^*) is plotted in Fig. 5.7. Figure clearly illustrate that the calculated cross-sections (lines) are in reasonable agreement with the available experimental data (filled symbols) for most of the cases. An important result that can be depicted from this figure is that the capture cross-sections (σ_{Cap}) for all the aforesaid reactions are in good agreement with the experimental data but there is some discrepancy in the fusion-fission cross-sections (σ_{ff}) for some reactions.

The σ_{Cap} as well as σ_{ff} data of $^{268}\text{Sg}^*$, $^{272}\text{Hs}^*$, $^{274}\text{Hs}^*$, $^{286}\text{Cn}^*$, $^{286}\text{Fl}^*$, $^{292}\text{Fl}^*$, $^{296}\text{Lv}^*$, and $^{302}120^*$ superheavy nuclei is reproduced well (see Figs. 5.7(c-e),(g-k)). On the other hand, for $^{264}\text{Rf}^*$, $^{265}\text{Db}^*$, and $^{273}\text{Mt}^*$, σ_{Cap} is fitted but σ_{ff} show deviation from experimental data. The σ_{ff} are overestimated for $^{264}\text{Rf}^*$ and $^{265}\text{Db}^*$ superheavy nuclei and underestimated for $^{273}\text{Mt}^*$ system as shown in Figs. 5.7(a-b), and 5.7(f) respectively. Interestingly, the experimental data available for these three systems is rather old [22] in comparison to other cases [2, 22, 29, 30, 37, 38]. The inconsistency in theoretically estimated fission cross-sections might be due to the anomaly in compound nuclear formation probability (P_{CN}) values calculated using

SECTION 5.2: CALCULATIONS AND RESULTS

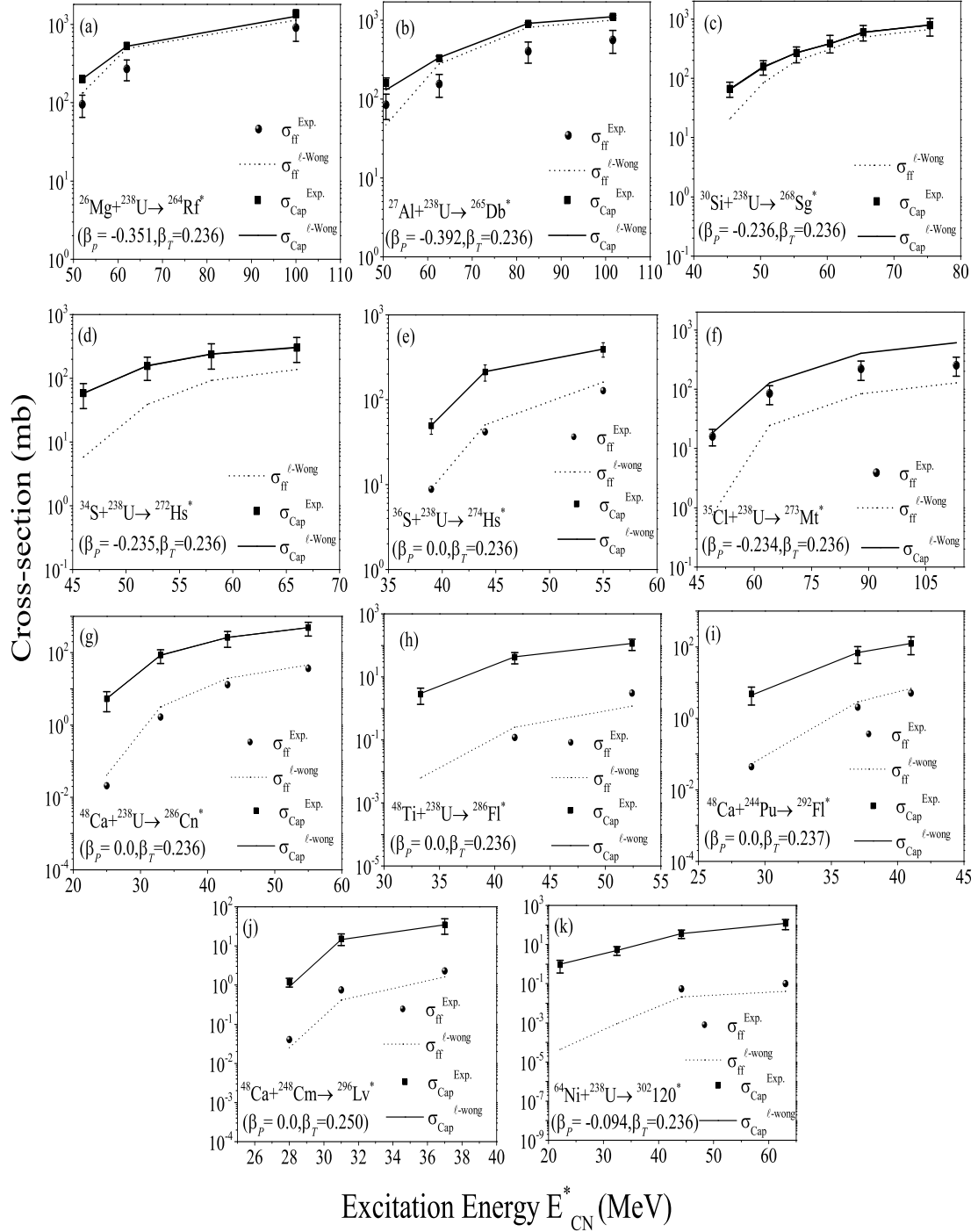


Figure 5.7: Comparison of experimental (symbols) and theoretically calculated (lines) capture (σ_{Cap}) as well as fusion-fission (σ_{ff}) cross-sections for Z=104 to Z=120 superheavy nuclei formed in different hot fusion reactions.

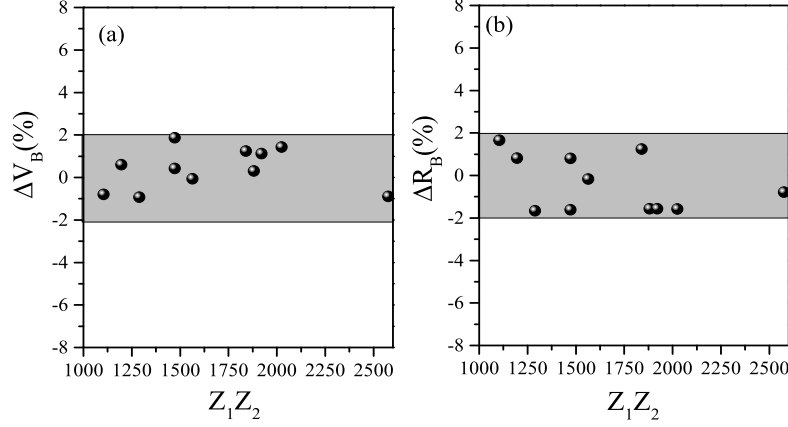


Figure 5.8: The percentage deviation of (a) barrier height (V_B) and barrier radius (R_B) from experimental numbers as a function of the charge product ($Z_1 Z_2$) by taking deformations up to β_2 at “optimum” orientations.

Eq. (2.47).

The comparative analysis of fusion barrier characteristics of considered reactions (in Fig. 5.7) is also worked out. The barrier characteristics are estimated by taking β_2 -deformations of nuclei with optimum orientations [41]. The measurement of position and height of Coulomb barrier in an experiment is a tedious task and the barrier characteristics mentioned in experimental work of Ref. [2, 22, 29, 30, 37, 38] are close to the one calculated using NRV code [42]. The percentage deviation of theoretical (ℓ -summed Wong model) and experimental Coulomb barrier height (V_B) and Coulomb barrier radius (R_B) is plotted in Fig. 5.8 as a function of charge product of incoming nuclei. The percentage deviation of Coulomb barrier height, ΔV_B (%) and Coulomb barrier radius, ΔR_B (%) is defined as

$$\Delta V_B(\%) = \frac{V_B^{Exp.} - V_B^\ell}{V_B^{Exp.}}; \Delta R_B(\%) = \frac{R_B^{Exp.} - R_B^\ell}{R_B^{Exp.}} \quad (5.1)$$

The theoretically calculated barrier heights (V_B) and radius (R_B) are in good agreement with available data [2, 22, 29, 30, 37, 38]. The calculated barrier parameters have accuracy of $\sim 98\%$ and can be reproduced in an approximate deviation range

of $\pm 2\%$. Conclusively, one can say that the ℓ -summed Wong model reproduces the barrier characteristics and hence the cross-sections quite adequately and can be used to make some relevant predictions.

(ii) Production of Z=107 (Bh), 109 (Mt), 110 (Ds), and 111 (Rg) superheavy isotopes

After comparing the barrier characteristics and cross-sections with available experimental data, the ℓ -summed Wong model is applied to study the least explored superheavy nuclei i.e. Z=107, 109, 110, and 111. The main aim of the present work is to predict the capture and fusion-fission cross-sections for different isotopes of superheavy nuclei. For the purpose, various t-p combinations are taken into account as shown in Table 5.2. The fusion barrier parameters (R_B , V_B) for the chosen reaction partners are tabulated in Table 5.2 along with deformations ($\beta_{\lambda i}$), Coulomb factor ($Z_P Z_T$), α_{BG} , η , and $|Q|$ -value. In case of superheavy nuclei, the chances of fusion are relatively less as compare to the lighter mass systems and it is hindered by quasi-fission (QF) events. Hence, all the above mentioned factors impart considerable significance in the estimation of fusion-fission cross-sections of superheavy nuclei.

Following observations can be withdrawn from Table 5.2: (i) The Coulomb barrier height (V_B) decreases with decrease in Coulomb factor ($Z_P Z_T$) and increase in mass-asymmetry (η). This ultimately effects the fusion (hence fission) cross-sections and these are expected to increase with increase in η . (ii) The Coulomb factor ($Z_P Z_T$) is associated with Coulomb repulsive energy in entrance channel and higher magnitude of Coulomb factor indicates the possible occurrence of quasi-fission (QF). According to Macroscopic-Microscopic model [43], if $Z_P Z_T > 1600$, QF events are more prominent. In Table 5.2, reactions are chosen in such a way that $Z_P Z_T$ of entrance channel lies across the aforesaid limit. The $Z_P Z_T$ for ^{48}Ti - and ^{48}Ca -induced reactions is above 1600 and the same for ^{24}Mg , ^{30}Si , and ^{36}S induced reactions is below this limit. This indicate that for more asymmetric reactions, there are higher

Table 5.2: ℓ -summed Wong calculated Coulomb barrier height (V_B), barrier position (R_B), along with deformations (β_{2i}), Coulomb factor ($Z_P Z_T$), Businaro-Gallone mass asymmetry (α_{BG}), entrance channel mass-asymmetry (η), $|Q|$ -value of entrance channel for the synthesis of $Z=107, 109, 110$, and 111 superheavy nuclei.

Reaction	β_{2i}	$Z_P Z_T$	α_{BG}	η	R_B	V_B	$ Q $
Z=107							
$^{48}\text{Ti} + ^{210}\text{At} \rightarrow ^{258}\text{Bh}^*$	(0.00,0.00)	1870	0.927	0.628	12.60	202.56	172.60
$^{48}\text{Ca} + ^{223}\text{Fr} \rightarrow ^{271}\text{Bh}^*$	(0.00,0.132)	1740	0.922	0.646	13.00	181.60	151.83
$^{36}\text{S} + ^{231}\text{Pa} \rightarrow ^{267}\text{Bh}^*$	(0.00,0.195)	1456	0.924	0.730	12.60	155.30	116.00
$^{31}\text{P} + ^{238}\text{U} \rightarrow ^{269}\text{Bh}^*$	(-0.218,0.236)	1380	0.923	0.769	12.20	152.30	98.61
$^{30}\text{Si} + ^{237}\text{Np} \rightarrow ^{267}\text{Bh}^*$	(-0.236,0.226)	1302	0.924	0.775	12.20	143.50	98.30
$^{24}\text{Mg} + ^{243}\text{Am} \rightarrow ^{267}\text{Bh}^*$	(0.393,0.237)	1140	0.924	0.820	11.70	128.70	75.52
Z=109							
$^{48}\text{Ti} + ^{223}\text{Fr} \rightarrow ^{271}\text{Mt}^*$	(0.00,0.132)	1914	0.929	0.645	12.90	199.90	161.20
$^{48}\text{Ca} + ^{227}\text{Ac} \rightarrow ^{275}\text{Mt}^*$	(0.00,0.164)	1780	0.927	0.651	13.00	186.12	157.00
$^{36}\text{S} + ^{237}\text{Np} \rightarrow ^{273}\text{Mt}^*$	(0.00,0.226)	1488	0.928	0.736	12.60	158.40	120.22
$^{35}\text{Cl} + ^{238}\text{U} \rightarrow ^{273}\text{Mt}^*$	(-0.234,0.236)	1380	0.928	0.743	12.30	171.10	116.20
$^{30}\text{Si} + ^{243}\text{Am} \rightarrow ^{273}\text{Mt}^*$	(-0.236,0.237)	1330	0.928	0.780	12.20	146.30	101.70
$^{24}\text{Mg} + ^{247}\text{Bk} \rightarrow ^{271}\text{Mt}^*$	(0.393,0.249)	1140	0.930	0.823	11.90	130.80	79.50
Z=110							
$^{48}\text{Ti} + ^{226}\text{Ra} \rightarrow ^{274}\text{Ds}^*$	(0.00,0.164)	1936	0.931	0.649	12.90	202.20	163.90
$^{48}\text{Ca} + ^{232}\text{Th} \rightarrow ^{280}\text{Ds}^*$	(0.00,0.205)	1800	0.929	0.662	12.90	187.34	159.03
$^{40}\text{Ar} + ^{238}\text{U} \rightarrow ^{278}\text{Ds}^*$	(-0.031,0.236)	1656	0.930	0.712	11.90	179.10	134.07
$^{36}\text{S} + ^{242}\text{Pu} \rightarrow ^{278}\text{Ds}^*$	(0.00,0.237)	1504	0.930	0.741	12.60	159.50	122.20
$^{30}\text{Si} + ^{248}\text{Cm} \rightarrow ^{278}\text{Ds}^*$	(0.0,0.235)	1344	0.930	0.784	12.20	147.50	103.30
$^{24}\text{Mg} + ^{251}\text{Cf} \rightarrow ^{275}\text{Ds}^*$	(0.393,0.250)	1140	0.931	0.825	11.80	132.20	81.40
Z=111							
$^{48}\text{Ti} + ^{227}\text{Ac} \rightarrow ^{275}\text{Rg}^*$	(0.00,0.164)	1958	0.934	0.651	12.80	204.80	167.90
$^{48}\text{Ca} + ^{231}\text{Pa} \rightarrow ^{279}\text{Rg}^*$	(0.00,0.195)	1820	0.932	0.656	12.90	190.00	162.30
$^{39}\text{K} + ^{238}\text{U} \rightarrow ^{277}\text{Rg}^*$	(-0.032,0.236)	1748	0.933	0.718	12.20	191.50	134.70
$^{36}\text{S} + ^{243}\text{Am} \rightarrow ^{279}\text{Rg}^*$	(0.00,0.237)	1520	0.932	0.742	12.60	161.80	125.00
$^{30}\text{Si} + ^{247}\text{Bk} \rightarrow ^{277}\text{Rg}^*$	(-0.236,0.249)	1358	0.933	0.783	12.20	149.20	107.10

SECTION 5.2: CALCULATIONS AND RESULTS

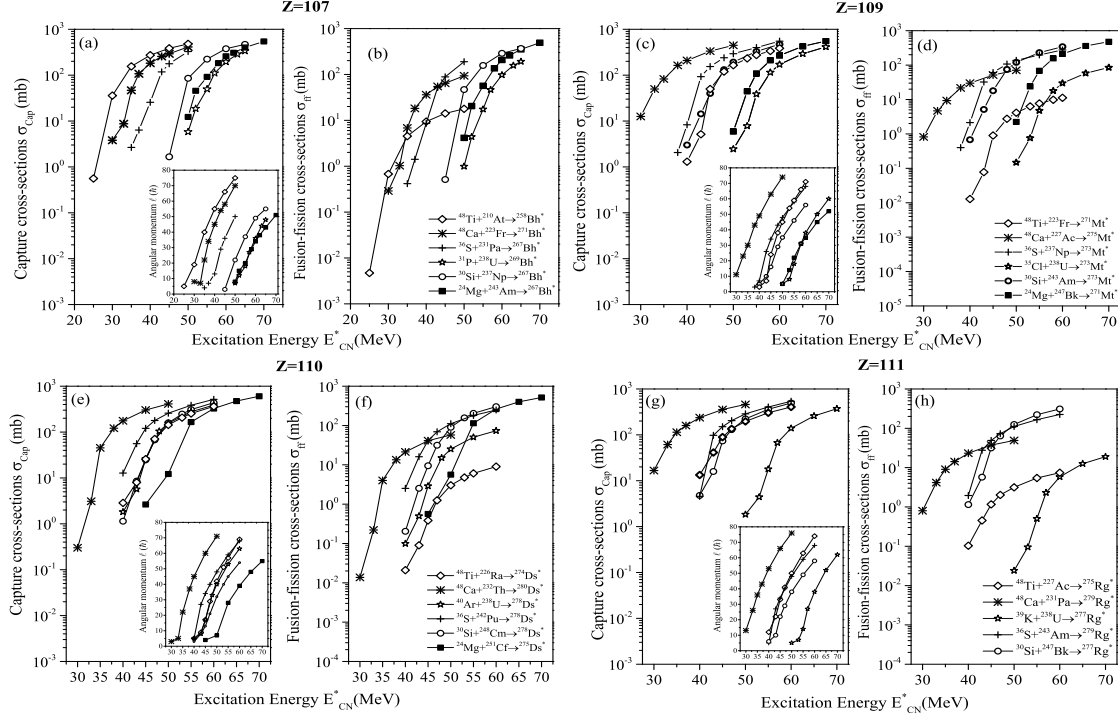


Figure 5.9: Theoretically predicted capture (σ_{Cap}) and fusion-fission (σ_{ff}) excitation functions for the synthesis of (a,b) $Z=107$, (c,d) $Z=109$, (e,f) $Z=110$, and (g,h) $Z=111$ superheavy nuclei. The respective ℓ -values are also shown in the inset of figures.

chances of fusion. Also, with increase in charge number (Z), the Coulomb factor ($Z_P Z_T$) for most of the reactions start approaching this threshold value. Conclusively, the symmetric interacting pairs generally lead to significant contribution of QF components. (iii) In asymmetric combinations of colliding nuclei, fusion suppression can also be observed due to the conditional barrier. So, for the case, Businaro-Gallone mass asymmetry point (α_{BG}) define the fusion process. Systems having $\eta \sim \alpha_{BG}$, there are higher chances of fusion. On contrary to this, for $\eta < \alpha_{BG}$, it is expected that fusion is not complete and there are chances of QF. For the reaction pairs mentioned in Table 5.2, $\eta < \alpha_{BG}$ and it is expected that QF may appear along with fusion-fission processes. The contribution of QF may be different for different channels depending on the deviation of η from α_{BG} and some other related factors.

The theoretically calculated capture (σ_{Cap}) and fusion-fission (σ_{ff}) excitation functions for the reaction partners mentioned in Table 5.2 are plotted in Fig. 5.9 for near and above barrier energies. Figs. 5.9(a,c,e,g) represent the capture cross-

sections and Figs. 5.9(b,d,f,h) shows σ_{ff} with respect to E_{CN}^* . The respective angular momentum values (ℓ_{max}) are plotted in the inset with E_{CN}^* . It is evident from this figure that, the variation of cross-sections is smooth with excitation energy. The cross-sections increases with energy and then start saturating. An important observation that can be noticed from this figure is that the magnitude of σ_{Cap} for the chosen reactions are quite close to each other. The comparison of σ_{Cap} at near barrier energies shows that the ratio of cross-section values for reactions with lowest mass-asymmetry to highest mass asymmetry (i.e. $\sigma_{Cap}^{\eta_{lowest}}/\sigma_{Cap}^{\eta_{highest}}$) is $\approx 1-2$. In contrast to above, the fusion-fission cross-sections are evidently different for the reactions under consideration. Higher fusion-fission cross-sections are observed for superheavy nuclei formed in ^{24}Mg -induced reactions followed by ^{30}Si and ^{36}S based reactions. The observed fission cross-sections are nearly identical for ^{30}Si and ^{36}S projectiles for most of the cases. Although the cross-sections are higher with ^{24}Mg , but still ^{36}S can be a preferable choice due to relatively lower excitation energies. Also, the reactions with doubly magic ^{48}Ca projectile have sufficiently large values with lower excitation energies which can be a good alternate for the synthesis of such nuclei. It can be used for the synthesis of neutron rich isotopes of respective nuclei. The least cross-sections are observed for the use of ^{48}Ti -induced reactions.

Fig. 5.10 is plotted to analyze the contribution of quasi-fission process towards capture cross-sections. The variation of σ_{Cap} and σ_{ff} is plotted with E_{CN}^* for two extreme mass-asymmetric reaction pairs leading to the formation of $Z=107$ (Bh) superheavy isotopes. Larger cross-sections are observed for $^{24}\text{Mg}+^{243}\text{Am}\rightarrow^{267}\text{Bh}^*$ reaction as compare to $^{48}\text{Ti}+^{210}\text{At}\rightarrow^{258}\text{Bh}^*$. The difference between σ_{Cap} and σ_{ff} is significantly large for ^{48}Ti -induced reaction and is observed least for the use of ^{24}Mg -projectile. For energies near the Coulomb barrier, the difference is higher as compare to the above barrier region. This deviation between cross-sections indicate the contribution of QF process. Hence one can say that the quasi-fission events are more pronounced for ^{48}Ti -projectile compared to others, which in turn further justify

SECTION 5.2: CALCULATIONS AND RESULTS

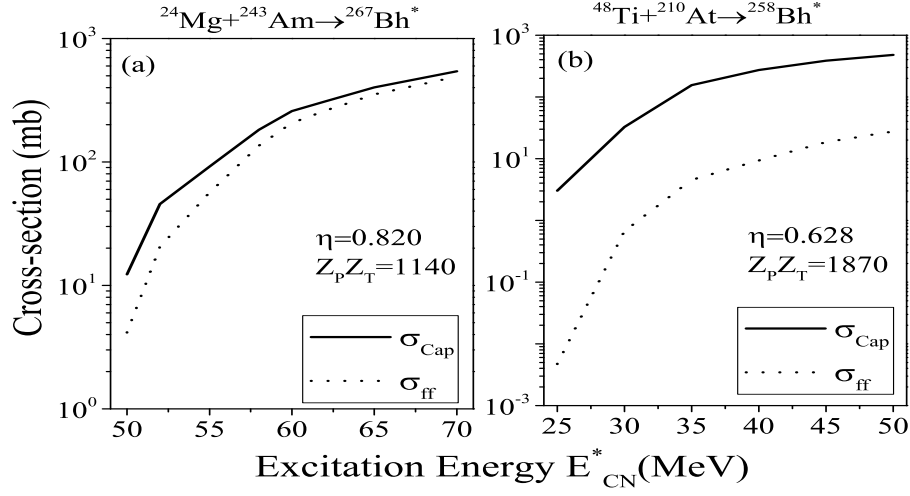


Figure 5.10: Variation of capture and fusion-fission cross-sections for $Z=107$ as a function of excitation energy (E_{CN}^*) for (a) $^{24}\text{Mg} + ^{243}\text{Am}$ (b) $^{48}\text{Ti} + ^{210}\text{At}$ reactions.

the above arguments. Similar type of results are observed for $Z=109$, 110 , and 111 superheavy nuclei which are not shown here to avoid repetition. This difference in σ_{Cap} and σ_{ff} is evidently caused by the corresponding change in P_{CN} value.

As mentioned in chapter 2, Eq. (2.47) determines P_{CN} for the reactions ends up with the emergence of heavy/superheavy nuclei. The calculated P_{CN} for different incoming channels are plotted in Fig. 5.11. P_{CN} is the measure of fusion suppression effects correlated with the entrance channel mass-asymmetry (η). Variation of P_{CN} is smooth and increases exponentially with E_{CN}^* . It becomes nearly constant at higher energies. Fig. 5.11(a) shows that, out of all the reactions under consideration for the synthesis of $Z=107$, the P_{CN} values are observed higher and comparable for $^{24}\text{Mg} + ^{243}\text{Am}$ and $^{30}\text{Si} + ^{237}\text{Np}$ reactions followed by $^{36}\text{S} + ^{231}\text{Pa}$. On the contrary, the least values are observed for $^{48}\text{Ti} + ^{210}\text{At}$. For $Z=109$ (see Fig. 5.11(b)), $Z=110$ (see Fig. 5.11(c)), and $Z=111$ (see Fig. 5.11(d)), the formation probability of ^{36}S and ^{30}Si induced reactions are comparable. Significant difference in the formation probability is observed for the interaction with ^{48}Ca and ^{48}Ti projectiles. The Coulomb barrier is larger and mass-asymmetry is lesser for the latter case. Hence lower P_{CN} values are observed for ^{48}Ti which in turn result in higher fusion hindrance as compare to

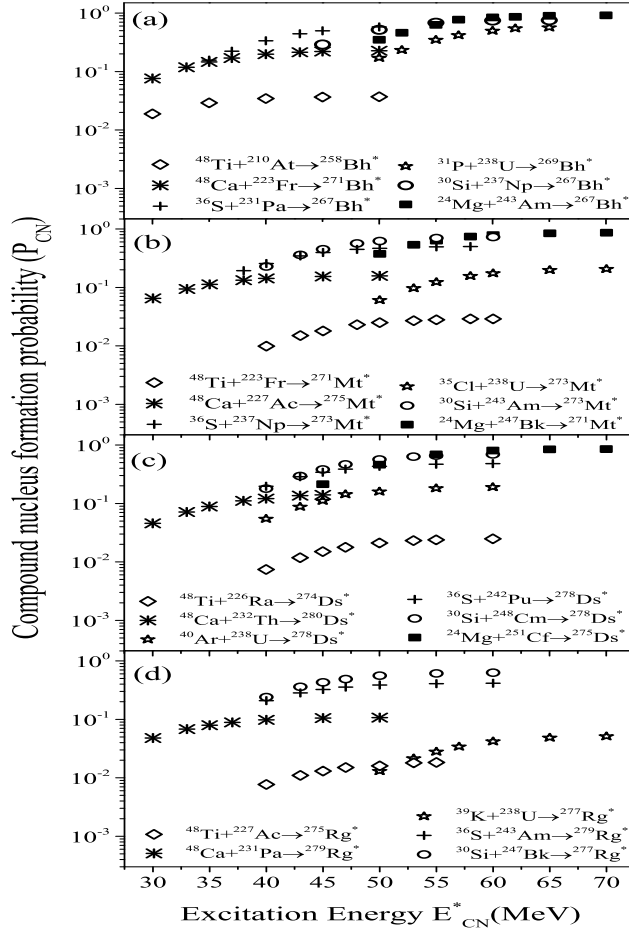


Figure 5.11: Compound nucleus formation probabilities (P_{CN}) plotted as a function of excitation energy (E_{CN}^*) for $Z=107, 109, 110$, and 111 superheavy nuclei formed via different entrance channels.

^{48}Ca projectile.

The respective orientations of the interacting nuclei also play notable part and effect the cross-section contribution significantly. The same is explored via Fig.6 which shows the variation of capture cross-sections (σ_{Cap}) at different orientation angles for $^{24}\text{Mg} + ^{243}\text{Am} \rightarrow ^{267}\text{Bh}^*$ reaction. Fig. 5.12(a-d) is plotted respectively for spherical+prolate, spherical+oblate, prolate+prolate, and oblate+oblate choices of interacting nuclei. The projectile angle (θ_P) is kept fixed at optimum orientation [41] and target angle (θ_T) is varied. It is observed that the capture cross-section is maximum at $\theta_T=0^\circ$ for prolate and $\theta_T=90^\circ$ for oblate nuclei. Also, the observed

SECTION 5.2: CALCULATIONS AND RESULTS

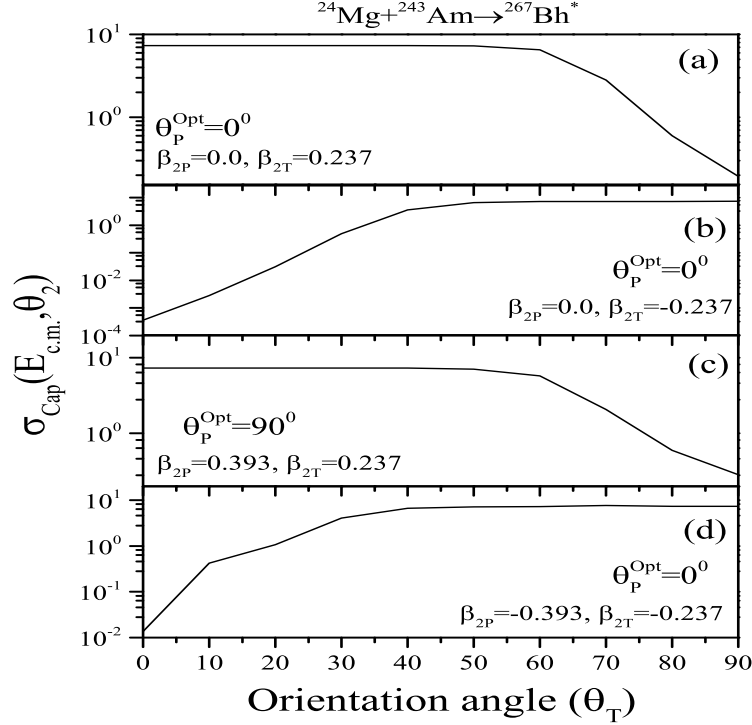


Figure 5.12: Variation of capture cross-section at each target angle (θ_T) for $^{24}\text{Mg}+^{243}\text{Am}$ reaction at energy near the Coulomb barrier ($E_{CN}^*=52$ MeV).

σ_{Cap} are slightly higher for deformed choice of nuclei relative to spherical+spherical (not shown here) and spherical+deformed pairs. This is possibly due to the fact that the deformation and orientation of nuclei change the balance between repulsive and attractive forces which ultimately effect the Coulomb barrier and hence the cross-sections.

Fig. 5.13 shows the variation of fission barrier heights (B_f) and neutron separation energy (B_n) with compound nucleus fissility parameter (x_{CN}). Experimental nuclear masses [44] are utilized for the estimation of neutron separation energies (B_n). The Möller and Nix masses of [45] are used where the experimental data is not available. Note that, the theoretical estimations of fission barrier for SHN are not yet very reliable and differ significantly for different choices of methodologies, therefore systematic study of such quantities is highly desirable. It is depicted from this figure that, with increase in proton number Z of nuclei, the compound nucleus fissility parameter (x_{CN}) increases. Higher values of x_{CN} suggest the higher chances

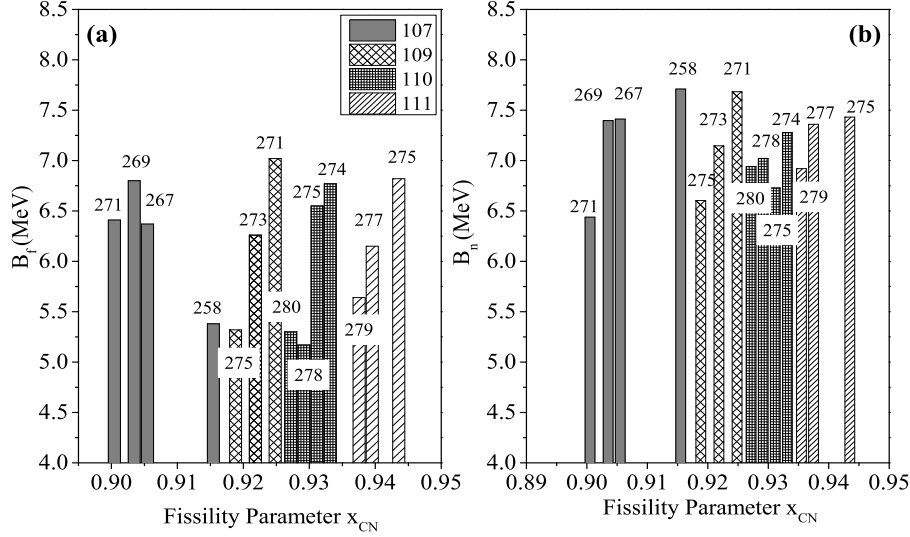


Figure 5.13: Variation of fission barrier heights (B_f) and neutron separation energy (B_n) as a function of compound nucleus fissility parameter (x_{CN}) for $Z=107, 109, 110$, and 111 superheavy nuclei.

of separation of a compound nucleus. Also, with increment in the mass of the superheavy isotopes, the fission barrier (B_f) decreases for most of the cases under consideration (see Fig. 5.13(a)). However, some uncertainty is observed for $^{269}\text{Bh}^*$ which is possibly due to the appearance of deformed neutron magic ($N=162$). The neutron separation energy (B_n) is plotted with x_{CN} in Fig. 5.13(b). The magnitude of B_n is relatively higher as compare to B_f for most of the cases which in turn suggest that fission is more prominent than the neutron evaporation process. The evaporation residue study of ^{36}S -induced reactions for $Z=109-111$ were explained in [36], so prime focus in this work is on fission and capture cross-sections only.

5.3 Conclusions

In this chapter, the fragmentation potential and preformation yields are calculated for $^{265}\text{Db}^*$ nucleus. Symmetric mass distribution of the fission fragments is noticed for the static-hot optimum orientation approach, suggesting that FF is the main decay mode for $^{265}\text{Db}^*$ compound nucleus. The potential energy surfaces (PES) of

$^{265}\text{Db}^*$ nuclear system are compared with the neighboring nuclei such as $^{264}\text{Rf}^*$ and $^{268}\text{Sg}^*$, resulting in similar symmetric fragmentation behavior. The peaks around Pb-region in the preformation yield do not have significant contribution towards the total cross-sections, hence the chances of QF channels are small when hot orientation approach is used. The dynamical deformations (T-dependent) are also applied to study the preformation yield of $^{265}\text{Db}^*$ nucleus, and relatively broad fission distribution is observed with fragments lying in the range $\frac{A}{2} \pm 25$. The small preformation probability of the peaks around $A_2=95$ in the hot static case gets significantly modified for the dynamical approach, which could be explained on the basis of the interplay between various attractive/repulsive interactions contributing towards fragmentation potential. Finally, asymmetric preformation distribution is obtained for the static cold approach at mass asymmetry $\eta=0.29$, resulting in a new fission region which is different from the traditional superheavy decay of fusion-fission ($\eta \sim 0$) and quasi-fission ($\eta \sim 0.4$). The dynamical deformations are also tested within the cold orientation approach, which give slightly modified preformation structure, where the contribution of symmetric fragments start dominating.

Beside this, the fission decay channel is investigated for $^{267}\text{Db}^*$ nuclear system formed in $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions. To compare the entrance channel relevance, the barrier characteristics are calculated for both reactions, resulting in lower barrier height for $^{18}\text{O}+^{249}\text{Bk}$ reaction. The capture and fusion cross-sections are predicted with Wong model. Higher σ_{fusion} are obtained for $^{18}\text{O}+^{249}\text{Bk}$ channel as compared to $^{19}\text{F}+^{248}\text{Cm}$, due to lesser Coulomb repulsion in the entrance channel. The P_{CN} for $^{18}\text{O}+^{249}\text{Bk}$ reaction is relatively larger as compared to $^{19}\text{F}+^{248}\text{Cm}$.

A systematic analysis of barrier characteristics, σ_{Cap} , and σ_{ff} is carried out at near and above the Coulomb barrier energies using the ℓ -summed Wong model and the experimental data is adequately addressed for $104 \leq Z \leq 120$ nuclei. Further, this approach is implemented to the estimations of capture and fission excitation functions for the isotopes of $^{258,267,269,271}\text{Bh}$, $^{271,273,275}\text{Mt}$, $^{274,275,278,280}\text{Ds}$, and $^{275,277,279}\text{Rg}$

nuclei. It has been observed that, the mass-asymmetric reactions involving ^{24}Mg , ^{30}Si , and ^{36}S projectiles seems more suitable to synthesize above mentioned superheavy isotopes. But due to lower excitation energy and higher cross-sections, ^{36}S can gain much attention. Beside this, the doubly magic ^{48}Ca provides an alternate option for the synthesis of neutron rich isotopes which result in enhanced cross-sections in comparison to ^{48}Ti projectile. Finally, an effort is made to analyze the endowment of FF and QF components. With increase in Z-number and hence Coulomb factor ($Z_P Z_T$), the deviation of η from α_{BG} increases, which indicate the enhanced contribution of QF events. For a given Z, the magnitude of σ_{Cap} is nearly same, whereas the σ_{ff} varies significantly suggesting different involvement of QF component.

The deformations and orientations play an important role in the determination of cross-sections. The cross-sections enhances with the involvement of deformations (as compare to spherical case). Motivating from this analysis, further in chapter 6, the role of entrance channel deformations and orientations on the barrier characteristics is explored. The main emphasis will be to analyze the role of β_2 , β_3 , and β_4 deformations on the barrier distribution.

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Chapter 6

Influence of higher order deformations on fusion dynamics

Preceding chapters were devoted to the study of evaporation residues (ER's) and fission dynamics over a wide range of superheavy nuclei. The nucleon evaporation and associated decay aspects were studied for hot and cold fusion reactions. As fission processes are major obstruction to the formation of ER's, hence the relative endowment of both processes with reference to various reaction parameters were investigated. Interesting results have been obtained from the study of potential energy curves, mass distribution, barrier characteristics *etc.* Moreover, the role of deformations and orientations was duly incorporated in the study which make out a very notable role in the reaction dynamics. The adoption of deformation and orientation degree of freedom in the previous chapters were limited to quadrupole (β_2) with optimum orientations only. In this chapter, the impact of higher order deformations (β_3 and β_4) is explored on the fusion dynamics and barrier characteristics of superheavy nuclei. For the purpose, ^{48}Ca induced hot fusion reactions (spherical+deformed) and ^{209}Bi based cold fusion reactions (deformed+deformed) have taken into account. A general description of the background employed for exploring the relevance of deformation effects and associated orientation criteria is outlined in the following sections.

6.1 Introduction

The importance of deformations in the formation of superheavy nucleus comes from the fact that lower fusion barriers are reported for deformed reaction partners in contrast to their spherical counter path. Along with the magnitude of deformations, the orientations of colliding nuclei impart a remarkable result on the fusion barrier height, and hence on the compactness of the nuclear configuration. For over the Coulomb barrier energies, compact configuration of the colliding nuclei is achieved mainly through the equatorial interactions, for which the probability of CN emergence is relatively high. On the other hand, pole-to-pole interaction is dominant in sub-barrier energies which may lead to the elongated dinuclear configuration. Such elongated systems follow quasi-fission and other non-compound nucleus (nCN) paths in competition to the fusion-fission processes [1,2]. In early 1980s, this research was stimulated by Greiner [3,4] while understanding the $^{238}\text{U} + ^{238}\text{U}$ dynamics where a specific orientation of colliding nuclei enhances the stability of nucleus. Experimentally, the concept of the compactness was first observed by Oganessian *et al.* in [5], followed by different authors [1,6–18]. In view of above results, the deformation and orientation effects are included in QMFT [19–21]. Within the framework of QMFT, the compactness of the nuclear systems is decided on account of the magnitude of quadrupole (β_{2i}) and hexadecupole (β_{4i}) deformations of reaction partners [11]. The results of this analysis show that: (i) for pure quadrupole systems and/or nuclei having significant quadrupole deformations with small (including -ve) hexadecupole structure prefer *equatorial compact (ec)* or *belly-to-belly compact (bbc)* configurations. It is relevant to mention that *deformed+deformed* interaction leads to *belly-to-belly compact* structure, whereas *spherical+deformed* pair forms *equatorial compact (ec)* shape. (ii) The quadrupole deformed nucleus with *large +ve hexadecupole deformations* leads to *non equatorial compact (nec)* or *not belly-to-belly compact (nbbc)/ near bbc* structures, depending on the magnitude of angular deviation.

It may be noted that, the interplay between the quadrupole and hexadecupole deformations is extremely important to realize the formation and subsequent dynamics of superheavy nuclei. The optimum orientations ($\theta=0^\circ$ or 90°) of colliding nuclei are decided based on the $\pm$ signs of the quadrupole deformations, if the influence of hexadecupole deformation parameter is rather small. The equatorial configuration ($\theta=90^\circ$) having highest barrier height and corresponding lowest radius is termed as “optimum hot” configuration. On the other hand, polar configuration is obtained for $\theta=0^\circ(180^\circ)$ with the lowest barrier (equivalently highest interaction radius) and refereed as “optimum cold” [9]. In order to avoid the confusion in terminology, they are also termed as polar and equatorial configurations. Further, the compact orientations of colliding reaction partners are obtained on the basis of both quadrupole and hexadecupole deformations. It is reported in [11], that the nuclei with $Z \geq 114$ follow the above criteria, because the targets used for the formation of $Z \geq 114$ superheavy nuclei have small hexadecupole deformations. On the other hand, for ^{48}Ca -induced reactions forming $Z < 114$ nuclei, the influence of the hexadecupole deformation of the targets is significant. For these nuclei, the compactness occurs at angles less than 90° . Such configurations give rise to non equatorial compact (nec) structure.

The previous analysis on the ^{48}Ca -induced reactions is mainly worked out for the even- Z superheavy nuclei [9, 11]. To conclude the aspect for whole superheavy mass range, in this chapter calculations are carried out for odd- Z nuclei. The effect of quadrupole and hexadecupole deformations is studied in reference to the compactness of odd- Z SHN synthesized in ^{48}Ca and ^{209}Bi induced reactions. Furthermore, the role of reflection asymmetric octupole deformations on the barrier profile is explicitly explored which was not done in the previous analysis. This study of compact behavior of colliding nuclei is important as it affects the relative emergence of different processes like quasi-fission, fusion-fission, evaporation residue *etc.* In order to proceed, $^{237}\text{Np} + ^{48}\text{Ca} \rightarrow ^{285}\text{Nh}^*$, $^{243}\text{Am} + ^{48}\text{Ca} \rightarrow ^{291}\text{Mc}^*$, and $^{249}\text{Bk} + ^{48}\text{Ca} \rightarrow ^{297}\text{Ts}^*$ reactions are analyzed using the extended fragmentation the-

ory. As the β_4 -deformation of ^{237}Np target nucleus is significantly large (compared to β_2 -deformation), as a result of this the non equatorial compact (nec) structure is observed. However, the magnitude of β_4 -deformation decreases with increase in the Z-number of the targets, leading to equatorial compact (ec) configurations, for $^{243}\text{Am}+^{48}\text{Ca}$ and $^{249}\text{Bk}+^{48}\text{Ca}$ reactions. In addition to this, the interaction of ^{209}Bi with Ti-Zn projectiles is also observed here to look for the change in compact angles of cold interaction processes. In particular, the ^{209}Bi -induced reactions are of significant interest, because for ^{209}Bi the distribution of the nucleons is slightly higher along the polar axis of the nucleus leading to weakly oblate structure [22]. Along with this, the magnitude of quadrupole and hexadecupole deformations (very small) is comparable for ^{209}Bi nucleus, but differs in sign. Hence instead of the treating ^{209}Bi spherical [23], if the small magnitude of the quadrupole and hexadecupole deformations is included then angles at which compactness occurs get modified significantly, leading towards not belly to belly compact (nbbc) configuration.

The theory of compactness can be further elaborated by including the reflection asymmetric octupole deformations. The inclusion of the octupole deformations of the target or projectile breaks the reflection symmetry in the distribution of the barrier height of the nucleus, which inturn modifies the compact angle. This is mainly because of competing octupole (β_{3i}) and quadrupole (β_{2i}) deformations, which may lead to nearly degenerate states [24, 25]. Broadly speaking, for nuclei beyond ^{208}Pb , the competition between the octupole (β_{3i}) and quadrupole (β_{2i}) deformations provokes the neutron and proton orbitals to come closer, and form the degenerate states. Hence the octupole deformation effects are of huge curiosity to comprehend the dynamics of the superheavy nuclei. The previous work applied for the superheavy reactions is mainly based upon the application of the quadrupole and hexadecupole deformations. Here, the effect of the octupole deformations on the collision of the heavy ions is explicitly explored.

6.2 Calculations and results

The present work is carried out by introducing two set of calculations. In the first set, the fusion dynamics of $Z=113$ superheavy nucleus is analyzed, in an attempt to address the relative analysis of hot and cold interaction processes. Here, $^{237}\text{Np}+^{48}\text{Ca}$ (hot fusion) and $^{209}\text{Bi}+^{70}\text{Zn}$ (cold fusion) reactions are studied using the extended fragmentation theory. We have estimated the compact structures for $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ superheavy nuclei using quadrupole (β_2) and hexadecupole (β_4) deformations. Then, we have calculated the compact angles for the various target-projectile combinations, anticipated for the formation of $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ nuclei. Moreover, the exclusive role of octupole deformations is also exercised in order to have better insight of dynamics involved. Subsequently, second set of calculations are carried out to generalize the fusion dynamics of odd- Z nuclei, ranging $Z=105-117$. Here also the ^{48}Ca and ^{209}Bi induced reactions are studied, for which various possible nuclear configurations are worked out. Depending on the deformations of projectile and target, various configurations can be possible, out of which few are shown in Fig. 1.4. Here, the ec/nec structures are shown for target and projectile heaving positive and zero quadrupole and hexadecupole deformations just to give an idea about different shapes used in further discussion.

$Z \geq 113$ nuclei are synthesized mainly via ^{48}Ca -induced interactions, whereas $Z \leq 113$ are formed using collision of Ti-Zn projectiles on ^{208}Pb and ^{209}Bi targets. As $Z=113$ nucleus is formed via ^{48}Ca as well as ^{209}Bi induced reactions, hence it provides the most suitable option to address the comparative analysis of the cold and hot fusion interactions. In view of this, the dynamics of $^{237}\text{Np}+^{48}\text{Ca} \rightarrow ^{285}\text{Nh}^*$ and $^{209}\text{Bi}+^{70}\text{Zn} \rightarrow ^{279}\text{Nh}^*$ reactions is studied. The most compact configuration of heavy ion reaction in hot as well as cold interactions is governed through the highest barrier and/or smallest radius of the colliding nuclei. As mentioned above, the extended fragmentation approach for deformed and oriented nuclei was applied earlier to frame the theory of compactness for ^{48}Ca -induced reactions forming even- Z

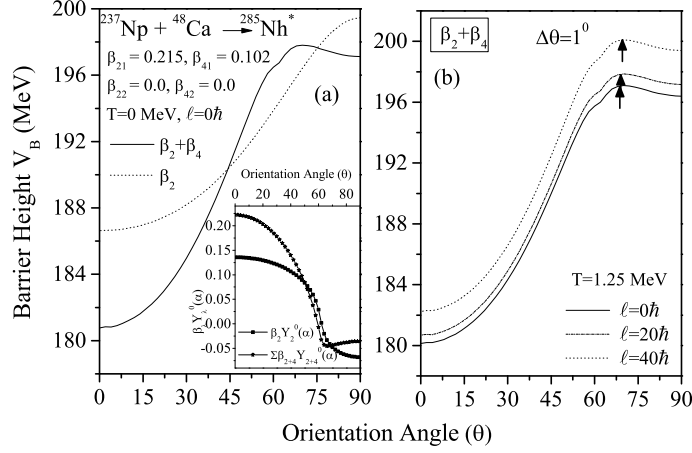


Figure 6.1: Variation of barrier height (V_B) as a function of orientation angle (θ) for (a) β_2 and $\beta_2 + \beta_4$ deformed nucleus at $T = 0$ MeV and $\ell = 0\hbar$ and (b) effect of angular momentum states on the barrier height with fixed magnitude of temperature, $T=1.25$ MeV.

nuclei [11]. The main focus here is to extend the same for the odd- Z cases, and analyze explicit role of quadrupole, octupole, and hexadecupole deformations. Fig. 6.1 shows the most compact configuration of prolate (^{237}Np)-spherical(^{48}Ca) system, where the variation of barrier height (V_B) with orientation angle (θ) is depicted. Since $^{285}\text{Nh}^*$ compound nucleus is formed via spherical projectile and β_2 -deformed target, so it is expected that equatorial compact (ec) configuration be achieved at $T=0$ and $\ell=0\hbar$. If one look at Fig. 6.1(a), it is clear that when deformations are included upto quadrupole (β_2) alone, the compact angle is obtained at 90° , showing ec configuration. At the same time, when higher order deformations are included upto hexadecupole ($\beta_2 + \beta_4$), the angle get shifted from 90° to 70° . The resulting configuration remains no longer ec but forms non-equatorial compact (nec) structure. The inset of Fig. 6.1(a) supports the above result, where the variation of spherical harmonic functions, required to address the radius parameters (Eq. (2.4)), are plotted with respect to the orientation angle. The minimum value of this function is obtained at 90° for β_2 deformed nucleus, which gets modified to $\sim 70^\circ$, if the same is addressed in $\beta_2 + \beta_4$ -deformed space. This result is in accordance to the previous

work [11], applied for the even-Z nuclei.

In order to analyze the angular momentum and temperature effect on the barrier height, and consequently on the compactness of the nuclear structure, Fig. 6.1(b) is plotted at $T \neq 0$ MeV and $\ell \neq 0\hbar$. For this, the temperature dependent potentials are used, as explained in chapter 2. To visualize the impact of angular momentum (ℓ) on the compactness, we have opted for fixed $E_{CN}^* = 39$ MeV (equivalently $T = 1.25$ MeV) in reference to experimental data of [26]. The angular momentum is varied from $0\hbar$ to $40\hbar$. Fig. 6.1(b) shows that the distribution of barrier with orientation angle follows the similar trend for different magnitudes of angular momentum. Although, with the addition of the angular momentum, enhancement in magnitude of barrier height is evident but the compact angle remains intact, reported $\sim 70^\circ$ for different ℓ values. It may be noted that the magnitude of radius parameter (Eq. (2.4)), required to calculate the centrifugal potential (V_ℓ) (Eq. (2.21)), remains fix for different angular momentum states and hence results in identical compact structure. The inclusion of angular momentum influences only the magnitude of centrifugal potential (V_ℓ) or barrier height, not the compactness of the nuclear structure. The similar trend is observed for $^{279}\text{Nh}^*$ nucleus, but not shown here to avoid repetition. Hence one may conclude that the angular momentum and temperature are not playing significant role to fix the compact angle of superheavy nuclei. Owing this, the subsequent analysis of odd-Z nuclei is being proceeded at $T = 0$ MeV and $\ell = 0\hbar$ consideration.

Following above, the variation of barrier height (V_B) with orientation angle (θ) for $^{209}\text{Bi} + ^{70}\text{Zn} \rightarrow ^{279}\text{Nh}^*$ reaction is presented in Fig. 6.2. Here, the most compact structure of $^{279}\text{Nh}^*$ nucleus is viable when β_2 deformed projectile and weakly deformed target respond to belly-to-belly compact (bbc) configuration [9]. The magnitude of β_2 -deformations for the target-projectile (t-p) combination is -0.008 and 0.045 respectively. However, the small magnitude of hexadecupole deformation (0.008) for ^{209}Bi looks comparable to the β_2 -deformation, but differs in sign. Due to this, the β_4 -deformations play significant role in fixing the compact angle, which for

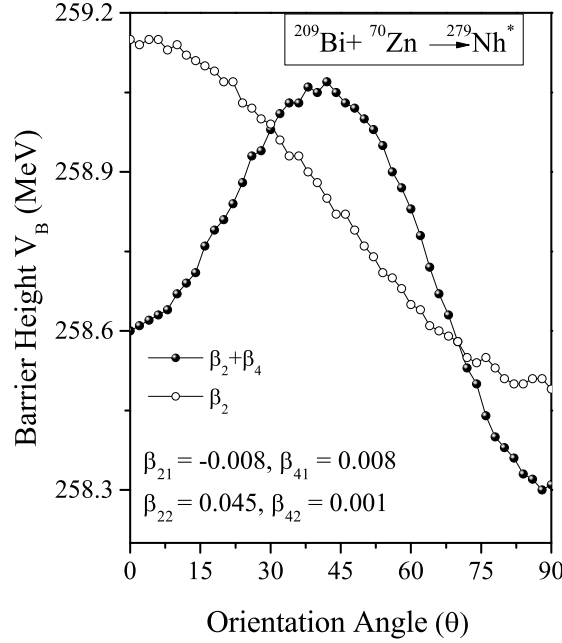


Figure 6.2: Barrier height (V_B) plotted with orientation angle (θ) for $^{209}\text{Bi}+^{70}\text{Zn}$ reaction, using β_2 and $\beta_2 + \beta_4$ deformations.

β_2 alone is obtained at θ^0 , as shown in Fig. 6.2. Hence with the incorporation of the β_4 deformations, the compact angle gets significantly changes to 42° , resulting in not belly-to-belly compact (nbbc) configuration. As mentioned in the previous section, the deformation effects are included from the tables of Möller *et al.* [22], in which slight oblate structure of ^{209}Bi is reported. On the other hand, if ^{209}Bi is taken as spherical [23], then according to above analysis, equatorial compact (ec) shape will be obtained. It is relevant to mention that $^{285}\text{Nh}^*$ nucleus shows deviation of $\sim 20^\circ$ (see Fig. 6.1(a)) from the equatorial compact (ec) shape when hexadecupole deformations are included. However, relatively larger deviation of the order of $\sim 42^\circ$ is observed for $^{279}\text{Nh}^*$ nucleus, formed in ^{209}Bi -induced reaction. This result is further explored in the later work, where different hot and cold fusion reactions leading to $Z_{CN}=105-117$ superheavy nuclei are addressed.

Further, using the fragmentation theory, the target-projectile (t-p) combinations for both hot and cold fusion reactions of deformed and oriented nuclei are determined. The (t-p) combinations refer to the minima(s) in potential energy surface

over cold one is also explained in [7] and discussed in previous chapters. Following outcomes can be portrayed from Fig.6.3(b) and 6.3(c): (i) For $^{279}\text{Nh}^*$ nucleus, as shown in Fig.6.3(b) in addition to experimentally used $^{209}\text{Bi}+^{70}\text{Zn}$ entrance channel, $^{206}\text{Pb}+^{73}\text{Ga}$, $^{193}\text{Ir}+^{86}\text{Kr}$, $^{231}\text{Np}+^{48}\text{Ca}$, $^{225}\text{Pa}+^{54}\text{Ti}$, and $^{221}\text{Ac}+^{58}\text{Cr}$ (t-p) combinations can also be taken as probable candidates to synthesize the superheavy compound nucleus. (ii) In a similar way, such minima can also be depicted from Fig. 6.3(c) using hot orientations for $^{285}\text{Nh}^*$ nucleus. Some asymmetric (t-p) combinations such as $^{231}\text{Pa}+^{54}\text{Ti}$, $^{229}\text{Ac}+^{56}\text{Cr}$, and $^{219}\text{Ac}+^{66}\text{Ni}$ are also observed as the minima(s) of the potential energy surfaces (PES). In addition to this, $^{208}\text{Pb}+^{77}\text{Ga}$ and $^{195}\text{Os}+^{90}\text{Rb}$ (t-p) combinations are of significant interest. In reference to this, Table 6.1 is presented in which various observed (t-p) combinations are shown along with the magnitude of deformations, barrier heights and compact angles etc.

Table 6.1 shows various (t-p) combinations for $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ nuclei obtained across the minima(s) of mass fragmentation yield. It is already mentioned that, spherical+deformed nuclei result in equatorial compact (ec) configuration, whereas deformed+deformed interaction pair forms belly-to-belly compact (bbc) configuration, shown for various (t-p) combinations in Table 6.1. Note that the slight variation in angle within 1^0 - 2^0 from optimum orientations, are also considered as equatorial compact and belly-to-belly compact structures. Conversely when the deviation is of the order of 5^0 - 6^0 , such structures are termed as near belly-to-belly compact configurations. Table 6.1 shows that $^{195}\text{Os}+^{90}\text{Rb}$ and $^{178}\text{Yb}+^{107}\text{Tc}$ form near belly-to-belly compact structure for $^{285}\text{Nh}^*$ nucleus, as the deviation is within $\sim 5^0$ - 6^0 range. Such configuration is also obtained for $^{279}\text{Nh}^*$ nucleus, for $^{193}\text{Ir}+^{86}\text{Kr}$ entrance channel. In addition to this, some structures are neither belly-to-belly nor equatorial compact due to large deviation from optimum orientations, such configurations are termed as nbbs and nec. As mentioned above, the experimentally measured entrance channel for $^{285}\text{Nh}^*$ i.e. $^{237}\text{Np}+^{48}\text{Ca}$ forms nec configuration, whereas nbbs structure is

Table 6.1: Target-projectile (t-p) combinations (A_1, A_2) referring to potential energy minima in Fig. 3 for $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ nuclei and their characteristic properties for hot orientations of fragments.

CN	Reactions	Deformations of (A_1, A_2)						Barrier properties			Compact angles		Remark
		β_{21}	β_{31}	β_{41}	β_{22}	β_{32}	β_{42}	V_B	R_B	θ_1	θ_2		
$^{285}\text{Nh}^*$	$^{237}\text{Np}+^{48}\text{Ca}$	0.215	0.0	0.102	0.0	0.0	0.0	197.80	12.65	70^0	s	nec	
	$^{231}\text{Pa}+^{54}\text{Ti}$	0.198	0.0	0.115	0.0	0.0	0.0	211.52	12.75	66^0	s	nec	
	$^{229}\text{Ac}+^{56}\text{Cr}$	0.189	-0.057	0.114	0.189	0.0	0.022	226.80	12.60	114^0	90^0	nbbc	
	$^{219}\text{At}+^{66}\text{Ni}$	0.103	-0.146	0.072	0.027	0.0	0.0	246.41	13.20	118^0	90^0	nbbc	
	$^{208}\text{Pb}+^{77}\text{Ga}$	0.0	-0.013	0.0	0.161	0.0	0.019	264.27	13.00	s	90^0	ec	
	$^{195}\text{Os}+^{90}\text{Rb}$	0.127	0.0	-0.068	0.089	0.0	-0.006	290.46	12.85	86^0	90^0	near bbc	
	$^{178}\text{Yb}+^{107}\text{Tc}$	0.279	0.0	-0.087	0.322	0.0	0.004	323.56	12.35	88^0	94^0	near bbc	
$^{279}\text{Nh}^*$	$^{145}\text{La}+^{140}\text{Ba}$	0.173	-0.128	0.079	0.0	0.0	0.0	324.41	13.30	110^0	s	nec	
	$^{231}\text{Np}+^{48}\text{Ca}$	0.208	0.0	0.117	0.0	0.0	0.0	198.84	12.60	68^0	s	nec	
	$^{225}\text{Pa}+^{54}\text{Ti}$	0.165	-0.133	0.112	0.0	0.0	0.0	209.51	12.85	116^0	s	nec	
	$^{221}\text{Ac}+^{58}\text{Cr}$	0.111	-0.144	0.081	0.199	0.0	-0.026	225.32	12.75	114^0	90^0	nbbc	
	$^{209}\text{Bi}+^{70}\text{Zn}$	-0.008	0.0	0.008	0.045	0.0	0.001	259.06	13.05	42^0	90^0	nbbc	
	$^{206}\text{Pb}+^{73}\text{Ga}$	-0.008	0.0	-0.008	0.071	0.0	0.010	265.05	13.00	0^0	90^0	bbc	
	$^{193}\text{Ir}+^{86}\text{Kr}$	0.136	0.0	-0.067	0.053	0.0	-0.007	291.14	13.80	86^0	92^0	near bbc	
	$^{155}\text{Eu}+^{124}\text{Sn}$	0.270	0.0	0.095	0.0	0.0	0.0	326.59	13.00	90^0	s	ec	
	$^{141}\text{La}+^{138}\text{Ba}$	0.0	0.0	0.0	0.0	0.0	0.0	323.99	13.40	s	s	spherical	

obtained for $^{209}\text{Bi} + ^{70}\text{Zn} \rightarrow ^{279}\text{Nh}^*$ reaction. Other (t-p) combinations corresponding to nec and nbbs are also given in Table 6.1. The above analysis for $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ nuclei shows that the comparable and reasonable magnitude of the hexadecupole deformations is responsible to modify ec, bbs nuclear structures to nec, nbbs configurations.

Further to obtain firm conclusion about the influence of deformations on the distribution of barrier, we consider one of the interacting nuclei as spherical and other having quadrupole, octupole, and hexadecupole deformations. Concerning this, the barrier height (V_B) is traced with respect to orientation angle (θ) of the deformed nucleus in Fig. 6.4. The orientation angle is varied from 0° to 180° . Broadly speaking, Fig. 6.4(a) is presented here for nuclei having β_2 -deformations only, whereas Fig. 6.4(b) and Fig. 6.4(c) are plotted respectively for β_3 and β_4 choice of deformation parameters. The magnitude of deformations is varied arbitrarily. Also the maximum reported values of β_2 , β_3 and β_4 are taken from Table 6.1, in order to observe the variation of barrier height with extreme deformation conditions. From this figure one may clearly see that the orientational distribution of barrier height is symmetric about 90° i.e. the variation of barrier from 0° - 90° is same as that from 90° - 180° when quadrupole (β_2) and hexadecupole (β_4) deformations are included. The overview of Fig. 6.4(a) and 6.4(c) shows that the maximum barrier height corresponds to particular orientation angle, lying in the range 0° - 90° . As evident, the same barrier height is observed at higher angles for 90° - 180° range. These two angles are mirror images of each other and can be connected by relation $180^\circ - \theta$. But the presence of octupole (β_3) deformation breaks the reflection symmetry of the barrier height as variation of barrier height is not symmetric about 90° (Fig. 6.4(b)). The maximum barrier is obtained at only one angle for the whole range of orientation angles varying from 0° to 180° . Due to this reason, the variation of angle for targets, reported in Table 6.1, is taken from 0° to 180° , which in the previous work was taken in the range of 0° to 90° [11]. Elaborating this, the octupole

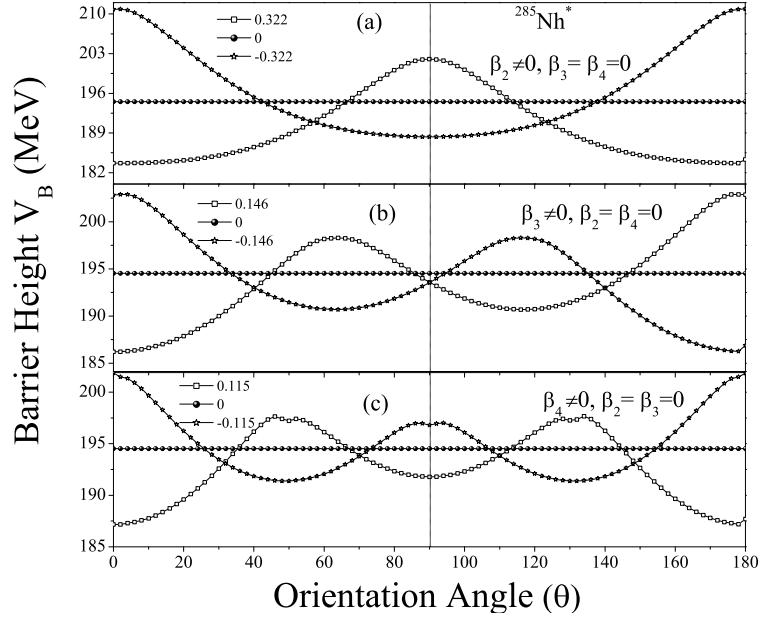


Figure 6.4: Distribution of barrier height (V_B) with orientation degree of freedom for deformed nuclear system $^{285}\text{Nh}^*$ by considering pure (a) quadrupole (β_2) (b) octupole (β_3) and (c) hexadecupole (β_4) deformations.

deformations of nuclei are generated by long range octupole-octupole interactivity among nucleons. A parity doublet is a trademark of octupole deformations and is defined as a pair of almost degenerate states [25]. The configurational rearrangement in these degenerate levels takes place in deformation space that breaks the reflection symmetry. So, from here one can conclude that whenever β_3 -deformations come into picture, it is advisable to explore the variation of barrier over whole range of orientation angles (i.e. 0° to 180°). Consequently, the compact angle is obtained in the range of $\sim 110^\circ$ - 118° for (t-p) combinations having β_3 -deformations as shown in Table 6.1. Additionally, the constant value of barrier height (V_B) is obtained for spherical nuclei, which is independent of the orientation angle, as shown by filled circles parallel to x-axis of the Fig. 6.4.

The various (t-p) combinations leading to different compact and non compact structures are discussed above, and the importance of β_3 -deformations is explicitly analyzed. In order to generalize these results, the Fig. 6.5 is plotted in which arbi-

trary variation in the magnitude of deformations provide a nice collective description of the above analysis. To achieve this, we plot Fig. 6.5, in which three different cases are discussed for $^{285}\text{Nh}^*$ nucleus formed via $^{237}\text{Np}+^{48}\text{Ca}$ entrance channel. Fig. 6.5(a) shows the variation of β_2 -deformed nucleus at the fixed magnitude of β_4 keeping $\beta_3=0$, Fig. 6.5(b) shows the variation of β_3 for constant magnitudes of β_2 and β_4 and finally Fig. 6.5(c) is plotted in which the variation of β_4 is included for constant values of β_2 . It is relevant to mention that Fig. 6.5(a,b,c) are plotted here to realize the importance of β_2 , β_3 and β_4 deformations respectively, on the compact angle of the colliding partners. Other combinations are also possible but here we focus only on these three cases. For each case, five different values with large, intermediate and negligible magnitude of deformations are included, to analyze the effect of deformations on the barrier height of the nuclei. Since projectile is spherical, so corresponding to the orientation angle of projectile, θ_2 is kept fix because for spherical system variation of barrier height with orientation angle is constant. The Fig. 6.5 shows strong dependence of deformations and orientations on barrier height (V_B).

First of all from Fig 6.5(a) following conclusions can be withdrawn: (i) In the presence of small +ve hexadecupole ($\beta_4 = 0.102$) with larger magnitude of +ve quadrupole deformation (prolate nucleus with $\beta_2=0.322$) equatorial compact configuration is obtained at $\theta=90^\circ(90^\circ)$.(ii) For intermediately prolate nucleus with $\beta_2=0.127$, having nearly same magnitude as that of hexadecupole deformation, the configuration is obtained at $\theta= 62^\circ(\text{or } 118^\circ)$, leading to nec structure. However, if the magnitude of quadrupole deformation decreases towards zero or -ve values (oblate structure), the presence of small +ve hexadecupole deformation influences the nuclear structure upto reasonable extend. As observed from Fig. 6.5(a), the nucleus with pure hexadecupole deformation with negligible magnitude of quadrupole deformation, the compact configuration is measured as $\theta = 46^\circ (134^\circ)$. Also, the oblate deformed nucleus with $\beta_2=-0.127$ having $\beta_4=0.102$, compact configuration is obtained at $38^\circ (142^\circ)$, which is further smaller than the above case. It is relevant

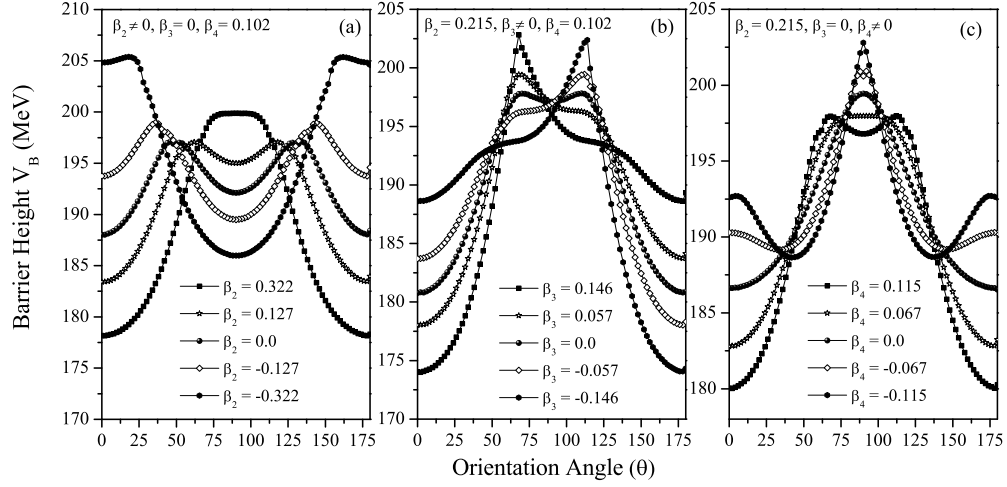


Figure 6.5: Variation of barrier height (V_B) as a function of orientation angle (θ) for $^{285}\text{Nh}^*$ nucleus having (a) different quadrupole deformations at $\beta_3=0$ and $\beta_4=0.102$ (b) different octupole deformations in addition to $\beta_2=0.215$ and $\beta_4=0.102$ (c) different hexadecupole deformations for fix $\beta_2=0.215$, with negligible magnitude of β_3 -deformation parameter.

to mention that when highly oblate structure is included (for fixed hexadecupole deformation), the compact angle starts approaching to 0° (180°). So from this figure it is clear that, compactness changes to 0° (180°) from 90° (90°) when the prolate systems are replaced with oblate-shaped nuclei.

Fig. 6.5(b) shows the orientational distribution of barrier height when nucleus has octupole deformations (β_3) in addition to the quadrupole and hexadecupole deformations. The barrier profile with β_3 is shown for fix magnitude of $\beta_2=0.215$ and $\beta_4=0.102$. The value of β_3 is varied from 0.146 to -0.146, chosen from Table 6.1. Since β_3 breaks the reflection symmetry, so the variation of V_B with θ is of much interest. The compact angles 66° , 68° , 70° (or 110°), 112° and 114° are calculated respectively for octupole 0.146, 0.057, 0, -0.057, -0.146 deformed nuclei. Interestingly, for +ve value of octupole deformations, the compact configurations are obtained for angles in the range 66° - 70° but as the sign of β_3 changes from +ve to -ve, the compact configuration shifts to 110° - 114° values of the orientation angles. Hence, the octupole deformation influences the compact configuration of the nuclei,

but elongated configuration remains intact for spherical-prolate system. Similar kind of results are also observed for $^{292}\text{Fl}^*$ formed in $^{244}\text{Pu}+^{48}\text{Ca}$ [12] reaction.

Although the importance of hexadecupole deformations is studied in the above discussion, yet other important results can also be drawn from Fig. 6.5(c). This figure is plotted for the fixed magnitude of quadrupole deformations with negligible contribution of β_3 . In view of the preceding discussion, significant change is observed in the barrier height distribution if the hexadecupole deformations are -ve instead of +ve and vice-versa. Elaborating this, when prolate deformed nucleus involved in the reaction has large +ve $\beta_4=0.115$ deformation then configuration is obtained at around 68° (112°), leading to nec structure. This result is same as that of Fig. 6.1(a), but with different magnitude of β_4 . The aim of this graph is to look for the modification of compact angles when the magnitude of the β_4 changes within the wide range. Indeed, as the magnitude of +ve β_4 gets reduced to 0.067 then compact angle approaches to 90° , called ec configuration. Hence Fig. 6.5(a,c) conclude that when the magnitude of the β_2 -deformation is larger than the β_4 -deformation, then ec configuration is obtained, which otherwise remains nec for higher magnitudes of β_4 in case of spherical-deformed nuclear systems. Further for -ve values of β_4 , the compact angle remains intact $\sim 90^\circ$, because the influence of β_4 -deformations on the compactness of the nuclear structure reduces significantly. In addition to this, the decreasing magnitude of β_4 plays important role to describe the elongated structures for spherical-prolate interaction pair. It is important to note that the elongated structures are obtained at 0° (180°) in Fig. 6.5(a) for +ve β_2 -deformed nucleus. However, these structures are significantly modified by introducing -ve values of hexadecupole deformations. It is clearly evident from Fig. 6.5(c) that 42° (138°) and 32° (148°) angles are observed respectively for $\beta_4=-0.115$ and -0.067 deformations, instead of 0° (180°).

Beside this, a comparative analysis of different odd-Z nuclei formed in ^{48}Ca and ^{209}Bi -induced reactions is also worked out. First of all, the comparison of

SECTION 6.2: CALCULATIONS AND RESULTS

Table 6.2: Angles corresponding to compact configuration of reactions with ^{48}Ca as projectile, colliding with ^{237}Np , ^{243}Am , and ^{249}Bk prolate-shaped targets resulting in $^{285}\text{Nh}^*$, $^{291}\text{Mc}^*$, and $^{297}\text{Ts}^*$ compound systems. Further ^{209}Bi induced reactions interacting with ^{50}Ti , ^{54}Cr , ^{58}Fe , ^{64}Ni , and ^{70}Zn projectiles giving odd-Z $^{259}\text{Db}^*$, $^{260}\text{Sg}^*$, $^{267}\text{Mt}^*$, $^{273}\text{Rg}^*$, and $^{279}\text{Nh}^*$ superheavy nuclei.

Z_{CN}	Reaction	(Target)			(Projectile)			θ_i^c	
		β_{21}	β_{31}	β_{41}	β_{22}	β_{32}	β_{42}	θ_1	θ_2
^{48}Ca-induced reactions:									
113	$^{237}\text{Np}+^{48}\text{Ca}\rightarrow^{285}\text{Nh}^*$	0.215	0.0	0.102	0.0	0.0	0.0	70^0	s
115	$^{243}\text{Am}+^{48}\text{Ca}\rightarrow^{291}\text{Mc}^*$	0.224	0.0	0.071	0.0	0.0	0.0	90^0	s
117	$^{249}\text{Bk}+^{48}\text{Ca}\rightarrow^{297}\text{Ts}^*$	0.235	0.0	0.040	0.0	0.0	0.0	90^0	s
^{209}Bi-induced reactions:									
105	$^{209}\text{Bi}+^{50}\text{Ti}\rightarrow^{259}\text{Db}^*$	-0.008	0.0	0.008	0.0	-0.02	0.0	42^0	178^0
107	$^{209}\text{Bi}+^{54}\text{Cr}\rightarrow^{260}\text{Sg}^*$	-0.008	0.0	0.008	0.180	0.0	0.045	42^0	90^0
109	$^{209}\text{Bi}+^{58}\text{Fe}\rightarrow^{267}\text{Mt}^*$	-0.008	0.0	0.008	0.199	0.0	-0.019	42^0	98^0
111	$^{209}\text{Bi}+^{64}\text{Ni}\rightarrow^{273}\text{Rg}^*$	-0.008	0.0	0.008	-0.087	0.0	-0.005	42^0	180^0
113	$^{209}\text{Bi}+^{70}\text{Zn}\rightarrow^{279}\text{Nh}^*$	-0.008	0.0	0.008	0.045	0.0	0.001	42^0	90^0

compact configurations of odd nuclei with $^{285}\text{Nh}^*$ ($Z=113$), $^{291}\text{Mc}^*$ ($Z=115$), and $^{297}\text{Ts}^*$ ($Z=117$) formed in ^{48}Ca -induced hot fusion reactions is shown in Table 6.2. In the chosen set of reactions, the projectiles are spherical and the targets are prolate deformed. It is important to mention here that with increase in Z -number of the deformed targets from $Z=113$ to 117 , the magnitude of quadrupole deformation (β_2) increases from 0.215 to 0.235. Also the magnitude of hexadecupole deformation (β_4) of the target nuclei decreases as we go from $^{285}\text{Nh}^*$ to $^{291}\text{Mc}^*$, and further to $^{297}\text{Ts}^*$ superheavy nucleus. The reported values are 0.102, 0.071, and 0.04 respectively for the above nuclei. Table 6.2 helps us to see the effect of increasing charge number (Z) on the compact configuration of the nucleus. From here, one can see that for $^{285}\text{Nh}^*$ nucleus, the compact configuration is obtained at orientation angle $\sim 70^0$, called nec configuration and as Z -increases from $Z=113$ to $Z=117$, the nec structure starts approaching towards ec (90^0). The reason lies in the fact that for $Z=113$ nucleus, the magnitude of the hexadecupole deformations is higher as compared to those

of $^{291}\text{Mc}^*$ and $^{297}\text{Ts}^*$. Relatively higher magnitude of β_4 deformations for $Z=113$ nucleus inturn modify the compact angle away from 90° . On the other hand the effect of β_4 -deformations is not much for $Z=115$ and $Z=117$ nuclei, hence the compact angle is decided only on the basis of β_2 -deformations, which is in accordance with previous work [11]. Hence the compactness for the ^{48}Ca -induced reactions can be generalized, by concluding the fact that, for odd- Z nuclei with $Z>113$, the equatorial compact (ec) structures are obtained. However, $Z=113$ favors nec structure. An overview of this study illustrates that, if the effect of β_4 -deformations is feeble, then the equatorial compact (ec) angle for spherical+deformed configuration can be decided only on the basis of the magnitude of β_2 -deformation.

In addition to the fusion dynamics of ^{48}Ca -based reactions (colliding with the prolate shaped actinide targets), the dynamics of Bi-induced reactions is also of much interest. The $Z<113$ nuclei are formed mainly in the cold fusion reaction synthesis in which ^{208}Pb and ^{209}Bi -targets are used. The orientational configuration of ^{208}Pb -induced reaction is quite different from that of reactions having ^{209}Bi -targets because of small difference in the magnitude of deformation values. In the present study, only Bi-induced reactions are discussed in Table 6.2, to generalize the compactness criteria for cold fusion reactions forming odd superheavy nuclei. The above analysis of $^{209}\text{Bi}+^{70}\text{Zn}\rightarrow^{279}\text{Nh}^*$ reaction supports nbhc structure due to comparable magnitude of β_2 and β_4 of ^{209}Bi target, with opposite sign. In order to understand this further, various Bi-induced reactions having different prolate and oblate shaped projectiles with smaller/larger magnitude of the hexadecupole deformations are chosen. It is relevant to mention that ^{209}Bi forms nearly spherical structure due to $Z=83$ and $N=126$, lying closer to spherical magic shell closures. Within the fragmentation approach, if ^{209}Bi is taken spherical than the equatorial compact (ec) or non equatorial compact (nec) configurations can be achieved, depending on the deformations of projectiles. However the small magnitude of the β_2 and β_4 deformation parameters of ^{209}Bi drags the structure towards nbhc configuration as compared to ec or

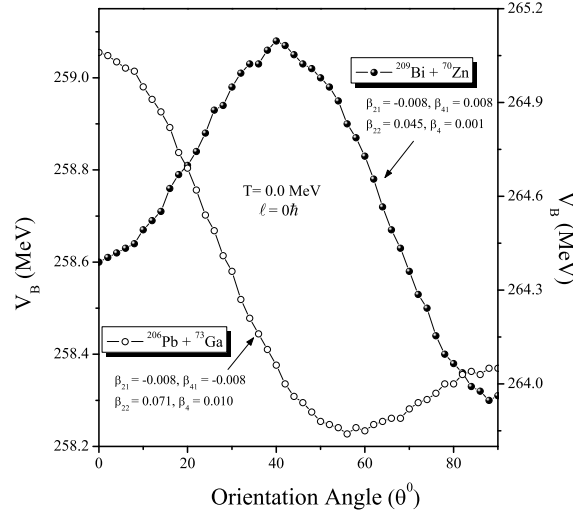


Figure 6.6: Comparison of compact behavior of two different reactions, i.e. $^{209}\text{Bi} + ^{70}\text{Zn}$ and $^{208}\text{Pb} + ^{73}\text{Ga}$ having comparable magnitude of β_2 and β_4 (for target nuclei) but of opposite signs and same signs of deformations respectively. Barrier height for reaction $^{208}\text{Pb} + ^{73}\text{Ga}$ is plotted on right vertical scale (open circles) and for $^{209}\text{Bi} + ^{70}\text{Zn}$ is plotted on left vertical scale (filled circles).

nec. In view of this if the deformations of ^{209}Bi are included, then the above table signifies that for all the ^{209}Bi -induced reactions, nbhc configurations are obtained. This result supports the conclusion of Fig. 6.2 in which compact angle is obtained around 42° , when the projectile is kept fixed and the target orientation is varied. In accordance to the deformations of the projectiles, various combinations of θ_c are obtained in which $\theta_1 = 42^\circ$ (corresponding to Bi) remains fixed and large variation in the magnitude of θ_2 (corresponding to projectile) can be seen. Hence one may conclude that for all ^{209}Bi -induced reactions (with ^{209}Bi taken as deformed nucleus) the nbhc structures are observed, independent of Z and A number of the projectiles.

Finally, to check the effect of Pb-targets on the compactness of the nuclear system formed in cold fusion synthesis, Fig. 6.6 is plotted, in which the comparison of the Pb and Bi-induced reactions is carried out. It is relevant to mention that though ^{208}Pb -target is used in the cold fusion reaction, but our prime focus is to study the compactness for the entrance channel which have identical β_2 and β_4

deformations. In order to do this, $^{206}\text{Pb}+^{73}\text{Ga}$ entrance channel is chosen from Table 6.1 in addition to $^{209}\text{Bi}+^{70}\text{Zn}$ leading to same $^{279}\text{Nh}^*$ nucleus. Fig. 6.6 illustrates that the compact angle shows large deviation from 0° for $^{209}\text{Bi}+^{70}\text{Zn}$ entrance channel. As mentioned above Bi have same magnitude of β_4 and β_2 deformations with opposite signs, hence nbcc structure is reported. Keeping the prolate shaped projectile intact with small β_4 deformations, if we switch the target's β_4 -deformation from 0.008 to -0.008, respectively for the Bi and Pb, the compact angle changes drastically from $\sim 42^\circ$ to 0° , giving rise to bbc structure. The previous work says that oblate-prolate compact shape is obtained at $\theta_1=0^\circ$ and $\theta_2=90^\circ$, if β_2 -deformations are included alone [9]. If +ve β_4 of Bi is added, then the compact angle is modified to $\sim 42^\circ$, however with -ve β_4 of Pb, the compact angle at $\sim 0^\circ$ is obtained, depending on the interplay between β_2 and β_4 deformations. Hence above analysis clearly signifies the importance of higher order deformations. Finally, the generalized form of different configurations to estimate the shape of the nucleus is presented in Table 6.3. The table is presented here for the spherical+deformed (prolate or oblate) and deformed+deformed particularly prolate+prolate cases. These systems are chosen in reference to the above studied reactions, particularly given in Table 6.1. It is relevant to mention that the oblate-oblate cases are not used here, because such interacting configurations are not viable for superheavy nucleus synthesis. On the other hand, the special cases are mentioned here to address the Bi and Pb induced reactions which form oblate-prolate configuration. Other possibilities for the oblate-prolate systems will be of interest for the future analysis.

6.3 Conclusions

In this chapter, the main interest is to check the compactness of odd nuclei formed via hot and cold fusion reactions. The magnitude of the both quadrupole and hexadecupole deformations portray impressive role in deciding the criteria of the compact angles for ^{48}Ca and ^{209}Bi -induced reactions. The ec and nec structures

SECTION 6.3: CONCLUSIONS

Table 6.3: Generalized form of different configurations measured for various interacting possibilities of nuclei, depending on the magnitude of the β_2 and β_4 deformation parameters.

β_2	β_3	β_4	Remark
spherical+deformed (prolate or oblate) nuclei			
$\beta_2=0$	$\beta_3=0$	$\beta_4=0$	spherical
		$\beta_4<0$	ec
		$\beta_4<<0$	ec
		$\beta_4>0$	nec
		$\beta_4>>0$	nec
$\beta_2>0$	$\beta_3=0$	$\beta_4=0$	ec
		$\beta_4<0$	ec
		$\beta_4<<0$	ec
		$\beta_4>0$ but $<<\beta_2$	ec
		$\beta_4>0$ but $\leq\beta_2$	nec
$\beta_2<0$	$\beta_3=0$	$\beta_4=0$	ec
		$\beta_4<0$	ec
		$\beta_4<<0$	ec
		$\beta_4>0$	nec
		$\beta_4>>0$	nec
Special case:			
$\beta_2=-X$		$\beta_4=-X$	ec or bbc
$\beta_2=-X$		$\beta_4=X$	nec or nbbsc
$\beta_2=0$	$\beta_3<0$	$\beta_4=0$	ec
	$\beta_3>0$		ec
$\beta_2>0$	$\beta_3>0$	$\beta_4>0$	nec with $\theta_c<90^0$
	$\beta_3<0$		nec with $\theta_c>90^0$
Prolate-Prolate deformed nuclei			
$\beta_{2i}>0$	$\beta_{3i}=0$	$\beta_{4i}>0$ but $<<\beta_{2i}$	bbc or near bbc
		$\beta_{4i}>0$ but $\leq\beta_{2i}$	nbbsc
		$\beta_{4i}<0$ or $\beta_{4i}<<0$	bbc or near bbc
$\beta_{2i}>0$	$\beta_{3i}<0$	$\beta_{4i}>0$ but $\leq\beta_{2i}$	nbbsc with $\theta_c<90^0$
	$\beta_{3i}>0$		nbbsc with $\theta_c>90^0$

are reported for spherical+deformed system, decided on the interplay of the magnitudes of quadrupole and hexadecupole deformations. Similarly nbbsc configurations are suggested for Ti-Zn+²⁰⁹Bi reactions. It is observed that, if β_2 deformed nucleus with smaller magnitude of the hexadecupole deformations are considered, the ec or bbc structures are reported, respectively, for spherical+deformed and deformed+deformed interacting pair. However, the comparable magnitude of hexadecupole deformations (with β_2 values) drags the nuclear structure from ec to nec and bbc to nbbsc structure. For ²³⁷Np+⁴⁸Ca (t-p) combination nec structure is reported, which otherwise remains ec for ²⁴³Am+⁴⁸Ca and ²⁴⁹Bk+⁴⁸Ca reactions. This is due to higher magnitude of hexadecupole deformations of ²³⁷Np target nucleus as compared to ²⁴³Am and ²⁴⁹Bk nuclei. Furthermore, with the interplay of quadrupole

and hexadecupole (β_2 and β_4) deformations, the inclusion of β_3 -deformations impart significant influence on the compact configuration. For spherical+deformed colliding nuclei with -ve β_3 , the compact angle is obtained at $\theta > 90^\circ$ and it shifts to $\theta < 90^\circ$ for +ve octupole deformations. Also the fragmentation potential (plotted using compact orientation), helps us to identify the new reaction partners for synthesis of $^{285}\text{Nh}^*$ and $^{279}\text{Nh}^*$ compound nuclei as listed in Table 6.1. The possibility of Ti and Cr induced reactions is also explored, which may be tested in the future experiment(s).

In chapters 3 to 6, numerous nuclear reactions and their related peculiarities are investigated conducive to recognize the dynamics of superheavy nuclei. The collective summery of the results discussed and conclusions drawn from them is briefed in the next chapter, and the scope of extension of this thesis work is outlined in the end.

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Chapter 7

Summary and Conclusions

In this thesis work, the Wong and ℓ -summed Wong models are employed along with DCM to analyze the fusion and decay dynamics of superheavy nuclei. The main motive of this work is to examine the capture, fission, and QF modes of SHN emerged via different heavy ion induced reactions. As the identification and differentiation between fission and quasi-fission mechanisms is the ongoing quest in this mass region, so both processes are analyzed in terms of temperature (T), angular momentum (ℓ), excitation energy, entrance channel effects, deformations, and orientations *etc.* The possibility of neutron evaporation is also explored for the studied nuclei in hot as well as cold fusion reactions. Beside this, a trial is made to look over the influence of static as well as temperature dependent deformations on the fragmentation path of superheavy nuclei (SHN). Additionally, the impact of optimum and compact orientations of colliding nuclei is also examined. Moreover, with the interpretation of excitation functions of some least studied SHN, we have tried to explore the yet unknown nuclear landscape. A concise overview of present research status of superheavy nuclei is discussed in **chapter 1**. Depending upon this, the objective of present thesis work are mentioned in the end of **chapter 1** along with the chapter wise logistics. The methodology which include the theoretical models (Wong, ℓ -summed Wong model, and dynamical cluster decay model (DCM)) is described in **chapter 2**. A detailed description of angular momentum, excitation energy, radius

parameters, different constitute of potentials, fusion, fission, and evaporation residue cross-sections is given in **chapter 2**.

Firstly, DCM is employed to evaluate the neutron evaporation decay of SHN formed via cold and hot fusion reactions. The relevant discussion about the same is given in **chapter 3**. For the purpose, σ_{1n} of nuclei with $Z=104-113$ formed in ^{208}Pb and ^{209}Bi based reactions are studied. The importance of hot and cold optimum orientations is figured out in view of the potential energy surface behavior. Interestingly, it is found that the hot orientation criteria is more suitable to address the σ_{1n} dynamics within DCM approach, as the potential energy minima appear at (t,p) combinations for these configurations. With the incorporation of β_{2i} deformations at hot optimum orientations, the experimental findings are in agreement with the theoretical calculations for $Z_{CN}=104-109$ nuclei. To fit the cross-sections of heavier nuclei ($Z_{CN}=110-113$), the fragmentation potential is modified by replacing I_S with I_{NS} . The σ_{1n} of all the nuclei i.e. $Z_{CN}=104-113$ are fitted within I_{NS} approach, which suggest that the use of I_{NS} seems better to apprehend the $1n$ -decay of SHN. In the end of **chapter 3**, the hot fusion reactions ($^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$) are considered to investigate the $4n$ and $5n$ evaporation residue cross-sections by employing I_S and I_{NS} approaches of MOI. Both I_S and I_{NS} approaches seem suitable to address the $4n$ channel cross-sections. At the same time, only I_{NS} could address the $5n$ cross-sections of $^{18}\text{O}+^{249}\text{Bk}$ reaction. Further, the fragmentation analysis of the $4n$ and $5n$ decays support prompt emission of $5n$ clusters.

After studying the neutron evaporation, the fission dynamics is explored in **chapter 4**. In the beginning of this chapter, FF and QF cross-sections are calculated for the decay of $^{286}112^*$, $^{292}114^*$, and $^{296}116^*$ superheavy nuclei formed in ^{48}Ca -based reactions. The $P_{CN}<1$ suggest that the quasi-fission competes with the compound nuclear fission process and the preformation probability peaks originating around Pb and Sn magic regions are used to identify the asymmetric and symmetric quasi-fission respectively. The DCM calculated FF and asymmetric QF cross-sections are in decent agreement with the experimental data. At above barrier energies, the

fragmentation potential, preformation factor, and penetration probabilities are compared for above mentioned SHN. This analysis suggest that the endowment of QF component increases with charge and mass of compound nucleus. The impact of different proximity potentials on the structural distribution is also exercised which suggest that, the preformation structure remains intact inspite of the different choices of proximity potentials. Also, the $\overline{TKE}$ distributions are explored by employing different proximity potentials out of which Prox-88 seems to provide better option at lower angular momentum and zero neck criteria ($\Delta R=0$).

Apart from this, the possibility of different fission decay dynamics of ^{238}U -based reactions ending up with the production of $Z=108, 112, 114$, and 120 superheavy nuclei is also examined in terms of hot and cold optimum orientations. The fragmentation and preformation structure show opposite trend with the use of aforementioned optimum orientations. It is important to note that mass yields calculated using hot criteria find good agreement with experimental counter path, so is applied to study the structure analysis of $Z=104-120$ superheavy nuclei near Coulomb barrier energies. A symmetric distribution is perceived for $Z=104-110$ nuclei with slight contribution of asymmetric quasi-fission. This distribution becomes highly asymmetric as one moves towards heavier elements (i.e. $Z=120$) which indicates higher chances of quasi-fission events. Also, the observed quasi-fission peak (around magic shells closure of Pb) shifts across different isotopes of Pb on moving from $^{264}\text{Rf}^*$ to $^{302}120^*$ superheavy nuclei.

The fission analysis is carried forward in **chapter 5** interms of dynamical (T-dependant) deformation effects on the fragmentation path. The fragmentation potential and preformation yield are calculated for $^{27}\text{Al}+^{238}\text{U}\rightarrow^{265}\text{Db}^*$ reaction by employing static hot and cold orientations as well as dynamic hot and cold orientations. A symmetric yield profile of fission fragments is perceived with static-hot optimum orientation approach advocating fusion-fission as the main decay mode for $^{265}\text{Db}^*$. A comparative analysis of potential profile for the aforementioned nucleus

is carried out with neighboring nuclei such as $^{264}\text{Rf}^*$ and $^{268}\text{Sg}^*$, resulting in similar symmetric fragmentation behavior. The application of dynamical deformations (T-dependent) on $^{265}\text{Db}^*$ nucleus results in relatively broader fission mass distribution in the range $\frac{A}{2} \pm 25$. Additionally, a significant enhancement of peaks around $A_2=95u$ is observed in case of hot dynamical approach which gets diminished for hot static case. This enhancement might be due to the interplay between various attractive/repulsive interactions contributing towards fragmentation potential. The choice of static cold orientation results in an asymmetric preformation (or fragmentation) distribution with peaks around mass asymmetry $\eta=0.29$. This new fission region is different from the traditional superheavy decay of fusion-fission ($\eta \sim 0$) and quasi-fission ($\eta \sim 0.4$). The dynamical deformations are also tested within the cold orientation approach, which give slightly modified preformation structure, where the contribution of symmetric fragments start dominating. In extension of above, the capture and fission excitation functions are calculated for $^{267}\text{Db}^*$ nuclear system formed in $^{19}\text{F}+^{248}\text{Cm}$ and $^{18}\text{O}+^{249}\text{Bk}$ reactions using Wong model. The $^{18}\text{O}+^{249}\text{Bk}$ reaction channel results in higher capture and fission cross-sections due to lesser Coulomb repulsion for the same. The P_{CN} values for $^{18}\text{O}+^{249}\text{Bk}$ reaction are also relatively large as compared to $^{19}\text{F}+^{248}\text{Cm}$.

Extending further, capture and fission cross-sections of some odd superheavy nuclei ($Z=107-111$) are predicted at near and above the Coulomb barrier energies using the ℓ -summed Wong model. Firstly, the experimental data is adequately addressed for $104 \leq Z \leq 120$ superheavy nuclei and then this approach is implemented to the estimations of capture and fission excitation functions of $^{258,267,269,271}\text{Bh}$, $^{271,273,275}\text{Mt}$, $^{274,275,278,280}\text{Ds}$, and $^{275,277,279}\text{Rg}$ isotopes formed via different hot fusion reactions. The mass-asymmetric reactions involving ^{36}S projectile seems more suitable to synthesize aforementioned superheavy isotopes due to lower E_{CN}^* and higher cross-sections. Alternatively, the doubly magic ^{48}Ca can be used to synthesize neutron rich isotopes. In the end, the relative contribution of fission and QF

components is analyzed for different incoming channels. It is observed that, with increase in Coulomb factor ($Z_P Z_T$) and deviation of η from α_{BG} , the involvement of QF component also get enhanced.

In all previous chapters, the study was constrained with the inclusion of deformation effects only up to quadrupole. In **chapter 6**, the impact of higher order deformations on the fusion mechanisms is worked out. The main interest of this chapter is to scrutinize the compactness of odd SHN emerged in hot (^{48}Ca induced) and cold (^{209}Bi based) fusion reactions. Depending on the magnitude of quadrupole and hexadecupole deformations, equatorial compact (ec) and non equatorial compact (nec) structures are reported for spherical+deformed system. Likewise, not belly to belly compact (nbbc) and belly to belly compact (bbc) configurations are suggested for deformed+deformed reaction pairs. It is concluded from the study that if β_2 deformed nucleus with smaller magnitude of the hexadecupole deformations (β_4) are taken into consideration, the ec or bbc structures are obtained. However, the comparable magnitude of β_2 and β_4 deformations gives nec and nbbc structures. Octupole deformations (β_3) in addition to the β_2 and β_4 impart significant influence on the compact configuration. Negative magnitude (-ve) of β_3 for spherical+deformed colliding nuclei gives compact angle $\theta > 90^\circ$ which shifts to $\theta < 90^\circ$ for +ve β_3 values. The barrier characteristics get notably swayed with the inclusion of higher order deformations and it will be of huge curiosity to estimate the fusion cross-sections by including the effect of individual deformation parameters.

The study of SHN have attracted huge attention of theoreticians as well as experimentalists working in the area of nuclear physics. The domain of superheavy nuclei is immensely exciting and interesting in numerous ways. The present thesis work is limited to the use of static Schrödinger wave equation, and it will be of further interest to use it by including the time co-ordinates. Apart from this, the methodology can be modified with the latest binding energies and deformation parameters so that appropriate analysis be made regarding stability aspects associated

with this extreme mass region. As evident from this study that deformations and orientations play significant part in the fusion dynamics of SHN, so it will be of further interest to study the effect of same on the estimation of compound nucleus formation probability (P_{CN}) and survival probability (P_{Surv}).