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Cluster decay analysis and related structure effects of fissionable heavy and superheavy nuclei

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Abstract. Collective clusterization approach of dynamical cluster decay model (DCM) has been applied to study the attributes of hot ($T \neq 0$) and rotating ($\ell \neq 0$) nuclei lying in heavy and superheavy mass regimes. We present here an overview of the characteristic fission decay properties such as shell effect, role of entrance channel, quadrupole (β_2) deformations and impact of hot (equatorial) compact orientation degree of freedom in comparison to cold (polar) elongated configuration. The presence of non-compound nucleus process, i.e., quasifission, is also investigated. Apart from studying the decay of excited state nuclei, the dynamics of heavy particle cluster emission is also addressed using the preformed cluster model (PCM).

Keywords. Collective clusterization; deformations and orientations; fission; heavy and superheavy nuclei.

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1. Introduction

In low-energy heavy-ion reactions ($E < 15$ MeV/A), a thorough description of decay mechanisms is quite desirable to have a comprehensive picture of reaction dynamics and related nuclear structure effects. In pursuant to achieve this, significant effort has been made using advanced experimental techniques and various theoretical approaches. In this work, we have applied the dynamical cluster decay model (DCM) [1–4] to study reaction dynamics of a variety of nuclear systems. Interestingly, the heavy and superheavy nuclei formed under extreme conditions of temperature, angular momentum, etc., exhibit different decay mechanisms which are helpful in providing furtherance to understand numerous nuclear properties and associated dynamical aspects. It has been observed that depending on its mass ($A_{\rm CN}$), the equilibrated compound nucleus (CN) may decay either through fusion–evaporation, equivalently light particles (LP; $A_2 \leq 4$) or through dominant fusion–fission process resulting in the emission of symmetric and/or asymmetric fission fragments. Apparently, instead of these decay modes resulting from fully equilibrated CN, there also lies the possibility of some competing non-compound nucleus (nCN) mechanism. Owing to reaction conditions and entrance-channel properties, nCN formed after the capture of the projectile and the target nuclei may reseparate prematurely giving rise to phenomena such as quasifission (QF), deep inelastic collision (DIC), etc. These nCN processes retain the history of formation, but differ in time-scale of emission, with QF taking relatively higher emission time. The QF process is observed in the decay of heavy and superheavy nuclei resulting from symmetric reactions while DIC is observed in reactions with asymmetric entrance channel and bridges the gap between CN and QF process.

This paper presents application of DCM [1–4] to heavy and superheavy mass nuclei for which fusion–fission and quasifission processes are dominant contributors towards the decay cross-sections. The role of quadrupole (β_2) deformations and entrance-channel effects are discussed for heavy mass ^{204}Po* nucleus formed in ^{16}O and ^{28}Si-induced reactions. In addition to this, a brief discussion regarding the systematics of odd-mass Fr isotopes is carried out by emphasizing on the shell closure effects of decaying fragments for ^{215}Fr* nucleus formed in ^{19}F and ^{18}O-induced reactions. Also, the effect of orientation degree of freedom is examined for superheavy ^{278,286}112* nuclei at extreme energies across the barrier and the contribution of QF component has been addressed. In DCM, ΔR represents the relative separation distance between two fragments or clusters A_i, which is supposed to assimilate the neck formation effects, and hence is termed as the neck-length parameter. It may be noted that DCM is a reformulation of preformed cluster model (PCM) [5–7] which is based on collective clusterization concept and helps to enhance our knowledge regarding the ground-state cluster emission from heavy parent nuclei. Using PCM, some signatures of heavy particle radioactivity are also addressed in the dynamics of superheavy mass region. In this paper, an effort is made to give an overview of decay patterns and related structure effects of fissionable nuclei which are carried out recently. This paper is organized as follows. The methodology including the effect of deformations and orientations is briefly discussed in §2. Results obtained therein are presented in §3 and conclusions drawn are summarized in §4.

2. The dynamical cluster decay model (DCM)

The DCM is based on the well-known quantum mechanical fragmentation theory (QMFT) [8] and is worked out in terms of collective coordinates of mass (charge) asymmetry, $\eta = (A_1 - A_2)/(A_1 + A_2)$ and relative separation R. It is a two-step model involving: (a) quantum mechanical preformation probability P_0 of the decay products or clusters formed in the mother nucleus and (b) penetration (P) of the fragments or clusters through the interaction barrier. The preformation probability (P_0) refers to η-motion, obtained by solving the stationary Schrödinger equation and is given as

$$P_0 = |\psi(\eta(A_i))|^2 \sqrt{B_{\eta\eta}} \frac{2}{A_{\mathrm{CN}}}. \tag{1}$$

The structure information of decaying nucleus is contained in P_0 via the fragmentation potential $V_R(\eta)$ which is the sum of temperature (T) dependent binding energies, Coulomb potential, proximity potential and angular momentum-dependent potentials. The quadrupole deformation ($\beta_{\lambda i}$) effects are also included along with the 'optimum' orientations taken from table 1 of [9].

The penetration probability P, which refers to R-motion is calculated using the WKB integral (details can be seen in [1–4]). The CN decay or fragment production cross-section for ℓ-partial waves is given by

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

Here μ is the reduced mass, m is the nucleon mass and $\ell_{\max}$ is the maximum angular momentum fixed at a point where light particle cross-section tends to zero. For PCM, the decay constant λ or decay half-life $T_{1/2}$ is defined as $\lambda = (\ln 2/T_{1/2}) = P_0 \nu_0 P$, where ν_0 is the assault frequency. The difference in DCM and PCM is that temperature effects are duly incorporated in former whereas they are silent in the latter.

3. Results and discussions

The fission cross-sections for heavy mass $^{204}Po^*$ system have been fitted in reference to [10], for spherical as well as β_2-deformed approach using only the model parameter, ΔR. For the comparison of the entrance channels, in figure 1, the fragmentation potentials are plotted for ^{16}O and ^{28}Si-induced reactions at $E_{\text{c.m.}} = 77.41$ and 119.06 MeV, respectively, representing common $E_{\text{c.m.}}/V_c$ ($\sim$1.05 MeV) value. The structure of potential energy surface (PES) is almost identical for both the channels, thus suggesting the absence of entrance-channel effect in the decay of heavy mass $^{204}Po^*$ nucleus. For both

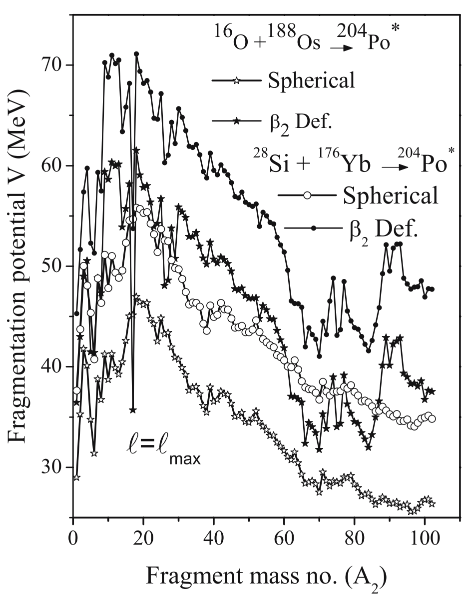

Figure 1. Fragmentation potential plotted as a function of fragment mass A_2, for the decay of $^{204}Po^*$ nucleus formed through ^{16}O + ^{188}Os and ^{28}Si + ^{176}Yb entrance channels.

Table 1. The fission cross-sections (σ_{fission}) estimated through DCM, for ^{211,219}Fr* isotopes, using systematics of ^{213,215,217}Fr* nuclei, at a common excitation energy $E_{\text{CN}} \sim 47$ MeV. The respective neck-length parameter and ℓ-values are also tabulated.

Compound nucleus	$E_{\text{c.m.}}$ (MeV)	T (MeV)	$\ell_{\max}$ ($\hbar$)	ΔR_{fiss} (fm)	$\sigma^{\text{DCM}}_{\text{fission}}$ (mb)	$\sigma^{\text{Expt.}}_{\text{fission}}$ (mb)
^{211}Fr*	81.84	1.437	118	0.950	22.93	–
^{213}Fr*	80.69	1.436	124	0.995	34.10	35.5
^{215}Fr*	79.37	1.428	136	1.07	169.00	168.8
^{217}Fr*	84.03	1.418	128	1.025	68.30	68.3
^{219}Fr*	84.38	1.410	123	1.00	16.48	–

spherical and deformed choices, relatively smaller magnitude of V (MeV) for heavy mass fragments ($A_2 > 60$), supports the dominance of fission decay channel. Moreover, for the fission region, a considerable change in structure from symmetric to asymmetric configuration is observed with the inclusion of deformations. These observations justify that the decay of heavy mass ^{204}Po* nucleus is significantly influenced by deformations while it is independent of entrance-channel effects. A part of these results is published in [1].

After observing the role of entrance channel and deformations for heavy mass ^{204}Po* nucleus, the estimation of fission cross-sections and shell closure effects in fission decay are analysed for odd mass Fr isotopes. Using the systematics of ^{213,215,217}Fr isotopes [2] at common $E^*_{\text{CN}} \sim 47$ MeV, the cross-sections for ^{211,219}Fr nuclei were estimated (see table 1). It is evident that the contribution of ^{211,219}Fr isotopes is rather small as compared to the experimentally measured ^{213,215,217}Fr isotopes. Further, figure 2 shows

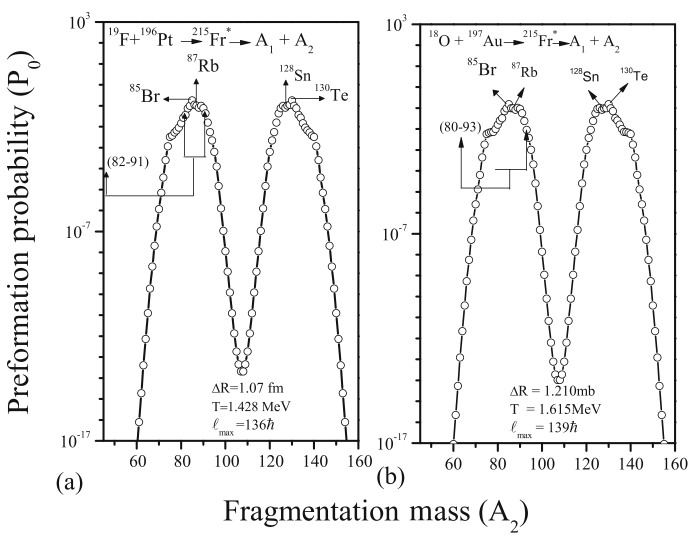

Figure 2. Shell closure effects represented by the variation of preformation probability P_0 plotted for ^{215}Fr nucleus formed in (**a**) ^{19}F + ^{196}Pt and (**b**) ^{18}O + ^{197}Au reactions.

the variation of preformation probability P_0 as a function of fragment mass A_i, for ^{215}Fr nucleus formed in ^{19}F + ^{196}Pt and ^{18}O + ^{197}Au reactions. It is observed that independent of entrance channel, the ^{215}Fr nucleus exhibits shell closure effects of decaying fragments, which are represented by double-humped structure having two strong maxima. This dual peak structure in the fissioning region is attributed to the deformed closed shell in the neighbourhood of light fragment charge $Z_2 = 36$ and spherical closed shell around heavy fragment $Z_1 = 50$. Interestingly, the emergence of shell closure effect is consistently applicable to all odd mass ^{211,213,217,219}Fr isotopes also, being dominant for lighter isotope ^{211}Fr and suppressed for the heavier one. The details of this work are published in [2].

In addition to this, we have extended our study to analyse the role of orientation degree of freedom on the decay of superheavy $^{278,286}112^*$ nuclei formed using ^{40,48}Ca + ^{238}U reactions in reference to [11]. For deformed actinide target, there lies a possibility that the projectile may hit the equatorial region of the target, thus forming the most compact configuration during CN formation. At above-barrier energies, the equatorial collisions are more probable, while the configuration may change to polar collisions at below-barrier energies. Figure 3 shows the comparison of hot (equatorial) compact and cold (polar) elongated orientation degrees of freedom at extreme energies across the barrier. It is observed that with the change from hot (figures 3a and 3b) to cold orientation (figures 3c and 3d), symmetric distribution changes to asymmetric and P_0 factor for both the nuclei decreases significantly, the suppression in magnitude being higher for $^{278}112^*$ nucleus. It may be noted that at below-barrier energies, the overestimated full momentum transfer cross-sections represent QF contribution and the same are tabulated in table 2. These results are partly published in [4].

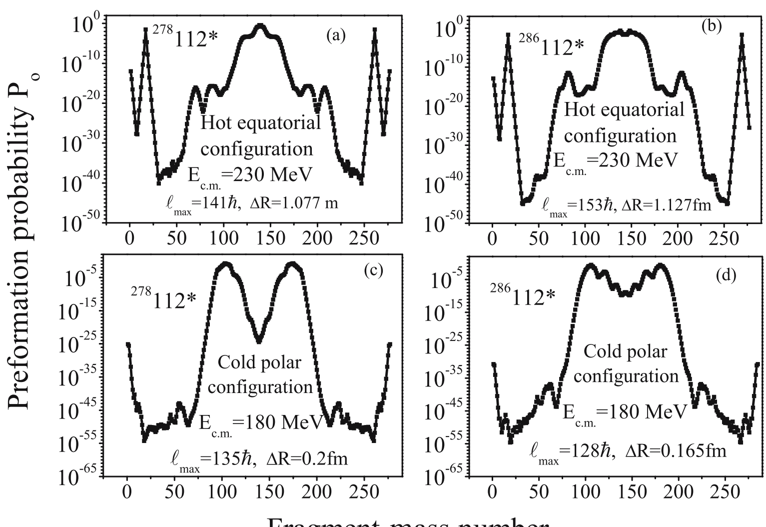

Figure 3. Preformation probability plotted as a function of fragment mass for $Z = 112$ isotopes at extreme energies across the barrier for (**a**, **b**) hot and (**c**, **d**) cold orientation degrees of freedom.

Table 2. The DCM-calculated full momentum transfer (fission + quasifission) cross-sections for ^{40,48}Ca + ^{238}U reactions. Also tabulated are the neck-length paramater ΔR, ℓ_{max} and the quasifission contribution for below-barrier energies.

Projectile	$E_{c.m.}$ (MeV)	ΔR_{fiss} (fm)	ℓ_{max} ($\hbar$)	σ_{FMT}^{DCM} (mb)	σ_{QF}^{DCM} (mb)	$\sigma_{Fusion}^{Expt.}$ (mb)
^{40}Ca	180	0.200	135	13.8	13.506	0.294
^{40}Ca	185	0.190	136	13.5	10.98	2.52
^{48}Ca	180	0.165	128	4.86	4.728	0.132
^{48}Ca	185	0.100	129	4.18	2.03	2.15

Table 3. The decay half-lives calculated using PCM for the most favourable fragments corresponding to a given fragment charge, compared with the available data.

			ASAFM		
Charge (Z)	Mass (A)	PCM (s)	AME11	KTUY05	LiMaZe01
113	278	12.96	12.18	13.75	13.15
115	287	5.03	6.45	5.55	4.36
115	288	8.04	8.10	7.80	5.39
115	289	1.30	5.31	5.33	2.07
117	293	−17.64	1.01	1.62	−2.27
117	294	−15.52	4.54	4.84	0.71

Finally, the PCM (the $T = 0$ and $\ell = 0$ form of DCM) is applied to explore heavy-particle radioactivity (heavy cluster emission) in superheavy regions. Table 3 shows variation of decay half-lives for the most favourable heavy clusters of $Z = 113, 115, 117$ isotopes using deformed choice of fragmentation. The PCM-calculated half-lives have been compared with the calculations of Poenaru *et al* [12], and the results obtained are found to be in reasonable agreement with the analytic superasymmetric fission model (ASAFM) for $Z = 113$ and 115 but it does not reinforce the cluster decay of ^{294,293}117 nuclei. However, the spherical approach (not shown here) works rather poorly, further indicating the importance of deformations for heavy-particle cluster emission in superheavy region.

4. Summary

The DCM was applied to study fission and quasifission processes observed in the decay of heavy and superheavy nuclei. It was observed that, the decay pattern of the heavy nucleus ^{204}Po* is independent of entrance channel whereas, it is significantly influenced by the inclusion of quadrupole (β_2) deformations. In addition to this, the importance of shell closure effect of decaying fragments was analysed in reference to odd mass Fr isotope formed in heavy-ion reactions. Also the role of hot and cold orientation degrees of freedom were witnessed at above- and below-barrier energies, respectively. Finally, the half-lives of heavy clusters emitted from superheavy nuclei signify the influence of deformation effects. Thus it may be concluded that both DCM and PCM suggest the importance of deformations and orientations to provide significant information regarding the reaction dynamics and the associated nuclear phenomena such as entrance channel, shell closure, fission, QF, cluster decay, etc.

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References

[1] M Kaur, R Kumar and M K Sharma, *Phys. Rev. C* **85**, 014609 (2012)
M Kaur and M K Sharma, *Phys. Rev. C* **85**, 054605 (2012)
[2] M K Sharma, S Kanwar, G Sawhney and R K Gupta, *Phys. Rev. C* **85**, 064602 (2012)
M K Sharma, G Sawhney, R K Gupta and W Greiner, *J. Phys. G: Nucl. Part. Phys.* **38**, 105101 (2011)
G Sawhney, G Kaur, M K Sharma and R K Gupta, *Phys. Rev. C* **88**, 034603 (2013)
[3] G Kaur and M K Sharma, *Nucl. Phys. A* **884**, 36 (2012)
G Kaur and M K Sharma, *Phys. Rev. C* **87**, 044601 (2013)
[4] K Sandhu, M K Sharma and R K Gupta, *Phys. Rev. C* **86** 064611 (2012)
K Sandhu, G Kaur and M K Sharma, *Nucl. Phys. A* **921**, 114 (2014)
[5] S S Malik and R K Gupta, *Phys. Rev. C* **39**, 1992 (1989)
[6] R K Gupta, in: *Heavy elements and related new phenomena* edited by W Greiner and R K Gupta (World Scientific, Singapore, 1999) Vol. II Chap. 18, p. 731
[7] S K Arun, R K Gupta, S Kanwar, B B Singh and M K Sharma, *Phys. Rev. C* **80**, 034317 (2009)
[8] J Maruhn and W Greiner, *Z. Phys.* **251**, 431 (1972)
M K Sharma, R K Gupta and W Scheid, *J. Phys. G* **26**, L45 (2000)
[9] R K Gupta *et al*, *J. Phys. G* **31**, 631 (2005)
[10] R Tripathi, K Sudarshan *et al*, *Phys. Rev. C* **79**, 064607 (2009)
[11] K Nishio, S Mitsuoka *et al*, *Phys. Rev. C* **86**, 034608 (2012)
[12] D N Poenaru, R A Gherghescu and W Greiner, *Phys. Rev. Lett.* **107**, 062503 (2011)
D N Poenaru, R A Gherghescu and W Greiner, *Phys. Rev. C* **85**, 034615 (2012)