Sequential decay mechanism of superheavy nucleus (Z=114): Evaporation Residues and successive decay chains

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Introduction

The superheavy nuclei (SHN) are synthesized either via 'cold' and 'hot' fusion processes. The isotopes with Z = 104 - 112 have been produced through the former process by using Lead 'Pb' or Bismuth 'Bi' as targets which are hit by different projectiles, like ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{62,64}Ni and ^{70}Zn [1]. On the other hand, the isotopes with Z>112 are induced via hot fusion by striking the beam of ^{48}Ca on deformed actinides such as ^{233,238}U, ^{237}Np, ^{240,242,244}Pu, ^{243}Am, ^{248,254}Cm, ^{249}Bk and ^{249}Cf [2]. In general, a superheavy compound nucleus (CN) is found in an unstable state and may results in a residual mass with the emission of light-particle. The residual nucleus may proceed via successive decay chains untill the stable product nuclei are formed. For an illustration, see the following reaction mechanisms followed by ^{288}Fl* SHN:

(I) Evaporation Residues
^{48}Ca+^{240}Pu→^{288}Fl* →^{285}Fl+3n
(II) α-decay chains
^{285}Fl→^{281}Cn+α; ^{281}Cn→^{277}Ds+α;
^{277}Ds→^{273}Hs+α; ^{273}Hs→^{269}Sg+α;
^{269}Sg→^{265}Rf+α
(III) spontaneous fission SF
^{265}Rf→ $A_1 + A_2$; $A_1 \approx A_2$

In the present work, we are interested to have an understanding of a sequential decay mechanism of ^{288}Fl* (Z=114), which is formed via the hot fusion reaction ^{48}Ca+^{240}Pu. The above analysis has been carried out with the use of collective clusterization approach developed on the basis of Quantum Mechanical Fragmentation Theory (QMFT) [4]. The obtained results in terms of cross-sections of ERs and half-lives of successive decay mechanisms have been compared with the available experimental data [3], in order to have a systematic analysis of neck-length parameter $\triangle R$. Note that, $\triangle R$ is the only parameter in the adopted collective clusterization approach. Beside this, we intend to explore the mass distributions of the first compound nucleus (^{288}Fl*), residual (^{285}Fl) and the end product of α- decay chain (^{265}Rf) in terms of the preformation probability, which imparts the relative structure information of decay fragments.

Methodology

In the Preformed Cluster-decay Model (PCM) with the inclusion of temperature effects ($T \neq 0$), the decay constant λ and half-life $T_{1/2}$ are defined as [5]

$$\lambda = \nu_0 P P_0; \;\; T_{1/2} = \frac{\ln 2}{\lambda}, \tag{1}$$

where P_0 is the preformation probability and P is the barrier penetrability that refer, respectively, to motions in mass asymmetry η [=$(A_1 - A_2)/(A_1 + A_2)$] and relative separation R. Here ν_0 is the barrier assault frequency. Equivalently, in the DCM, the CN decay cross-section is defined as

$$\sigma_0 = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{max}} (2\ell+1) P_0 P; \;\; k = \sqrt{\frac{2\mu E_{c.m}}{\hbar^2}}. \tag{2}$$

Important to mention that, both the PCM(T) and DCM models are based on the collective clusterization approach.
For α-decay of the recoiled superheavy nucleus, the temperature T (in MeV) is related to its excitation energy E^*_R as

$$E^*_R = \frac{1}{10} A T^2 - T, \tag{3}$$

where $E^*_R = E_R + Q_\alpha$. Here, Q_α denotes the Q value of α decay, and for the recoil energy E_R we take the value from experimental data. On the other hand, for SF, $E^*_R = E_R - Q_\alpha$.

Results and discussion

In the present work, we have studied a sequential decay mechanism within the framework of collective clusterization approach. Initially, we have estimated the ER cross-sections for ^{288}Fl* →^{285}Fl*+3n reaction at $E_{c.m.}$= 207.5 MeV

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(I) Evaporation Residues (ER)					
Compound nucleus	$E_{c.m.}$ (MeV)	T (MeV)	$\triangle R$ (fm)	Cross-sections (mb) Theo.	Expt.
^{288}Fl*	207.5	1.390	1.05	5.5×10^{-10}	5.8×10^{-10}
(II) α-decay chain					
Parent Nucleus	E_R^* (MeV)	Decay Mode	$\triangle R$ (fm)	Half-life $T_{1/2}$ (s) Theo.	Expt.
^{285}Fl	15.10	α	0.86	0.09	0.10
^{281}Cn	16.93	α	0.97	0.20	0.18
^{277}Ds	19.20	α	0.98	0.004	0.004
^{273}Hs	20.50	α	0.92	0.59	0.52
^{269}Sg	21.40	α	0.88	995	840
(III) Spontaneous Fission (SF)					
^{265}Rf	6.56	SF	0.83	69	66

TABLE I: The ER cross-sections and half-lives $T_{1/2}$ (s), for α-decay chains and spontaneous fission (SF) mechanisms followed by ^{288}Fl* SHN, and corresponding neck-length prameter $\triangle R$ (fm). The experimental data [3] is also shown for comparison.

and compared the results with the available experimental data [3], as shown in Table I. Further, we have obtained the half-lives ($T_{1/2}$) of α-decays proceeded by the superheavy residual (^{285}Fl) and successive product nuclei. This chain ends when the spontaneous fission (SF) starts dominating over α-decay mechanism. Here, the end product of α-decay chain ^{265}Rf disintegrates further into two nuclei of almost similar masses. In Table I, the theoretically obtained $T_{1/2}$ for the successive decay chains are shown and find good agreement with the experimental data [3]. With this comparative analysis, we have found a systematic trend in the neck-length parameter $\triangle R$. It is observed that $\triangle R$ is highest for ER emission and decreases as we proceed towards successive α-decay and SF channels.

On the basis of above analysis, we have studied the mass distributions in terms of preformation probability P_0 for SH nuclei, i.e. ^{288}Fl* (compound nucleus), ^{285}Fl (residual nucleus) and ^{265}Rf (leading SF), mainly in the fission regions within the framework of collective clusterization approach. These regions are marked in Fig.1. The fission fragments (*ffs*) follow the symmetric fragmentation, but the fissioning region becomes narrower as one moves towards the SF decay mechanism. Note that, along with the peaks observed for *ffs*, there is an emergence of heavy-mass fragments (*HMF*) due to possible presence of shell closure and deformation effects. However, the symmetric peak of *ffs* is always dominant. Because the binding energies of symmetric fission fragments is relatively higher than that of *HMFs*. One may conclude that for Z=114 SHN, a symmetric fission distribution is observed independent of the chosen set of decay mechanisms.

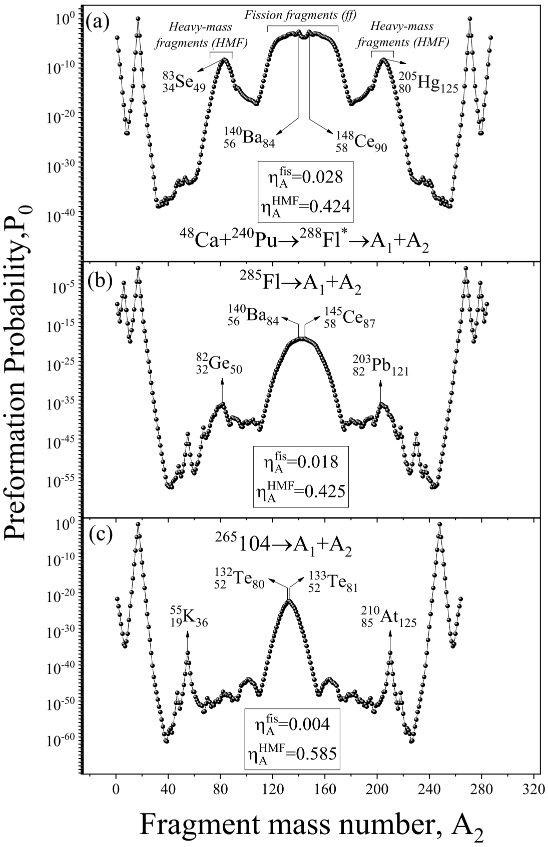

FIG. 1: The mass distributions of (a) ^{288}Fl* compound nucleus (formed via ^{48}Ca+^{240}Pu reaction), (b) ^{285}Fl residual element (leading α-decay chain) and (c) ^{265}Rf (end product of α-decay chain) are shown as a function of decaying fragment mass number, A_2.

References

[1] S. Hofmann and G. Munzenberg, Rev. Mod. Phys. **72**, 733 (200).

[2] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **87**, 054621 (2013).

[3] V. K. Utyonkov *et al.*, Phys. Rev. C **97**, 014320 (2018).

[4] R. K. Gupta, *Heavy Elements and Related New Phenomena*, edited by W. Greiner and R. K. Gupta (World Scientific, Singapore, 1999), Vol. I and II.

[5] Niyati *et al.*, Phys. Rev. C **91**, 054606 (2015).