Vol. 48 (2017) *ACTA PHYSICA POLONICA B* No 3

ANALYSIS OF SPONTANEOUS FISSION IN SUPERHEAVY MASS REGION USING THE DYNAMICAL CLUSTER-DECAY MODEL*

Gudveen Sawhney, Amandeep Kaur, Manoj K. Sharma

School of Physics and Materials Science, Thapar University, Patiala, India

Raj K. Gupta

Department of Physics, Panjab University, Chandigarh, India

(Received December 14, 2016)

Based on the dynamical cluster-decay model (DCM), we have extended our earlier study on α-decay chains of superheavy nuclei (SHN), to address the phenomenon of spontaneous fission (SF) in ^{267}Rf occurring as an end product of the decay chain of $^{291}116^*$ formed via ^{245}Cm+^{48}Ca reaction after $2n$ emission. Interestingly, the most probable decay fragment ^{133}Te (and the corresponding daughter ^{134}Te) lie in the neighborhood of doubly shell closure, which in DCM is justified in terms of a minimum in fragmentation potential and the maximum in preformation factor. The half-life times are estimated using β_2-deformed choice of fragments, with calculated half-lives finding decent agreement with available experimental data.

DOI:10.5506/APhysPolB.48.629

1. Introduction

Spontaneous fission (SF) is one of the most prominent decay modes, energetically feasible for both heavy and superheavy nuclei. In general, the superheavy nuclei (SHN) are governed via sequential α-decay chains from unknown nuclei to known nuclei, usually ending with a stable nuclear system or as a spontaneously fissioning nucleus. The α decay and SF can be considered as the limiting processes that determine the stability of nuclear systems in the extreme mass region. Beside this, β decay could be another possible decay mode for the SHN lying beyond the β-stability line. However, since the β decay proceeds via a weak interaction, this process is slow and relatively less favored. Also, the energy involved (released) in β-decay process is many factors smaller as compared to that for SF and α decay.

---

[*] Presented by G. Saxena at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 28–September 4, 2016.

Experimentally, the SF and α-decay half-lives of several SHN have been measured by different groups to explore the possibility of finding the long-lived elements in superheavy mass region. Theoretically, both these processes share the same underlying mechanism, *i.e.*, the fragment preformation and quantum tunneling effects. In order to understand any phenomena and underlying experimental results, a detailed analysis is required using appropriate theoretical approach. In the present study, we have made an attempt to analyze the SF half-life of ^{267}Rf occurring as the end product in the decay chain of $^{291}116^*$ formed via $2n$ emission of the compound nucleus (CN) formed in $^{245}\mathrm{Cm}+^{48}\mathrm{Ca}$ reaction. The calculations have been performed for quadrupole deformed (β_2) choice of fragments, within the dynamical cluster-decay model (DCM) [1] for angular momentum $\ell = 0$ case. Note that the DCM ($\ell = 0$) is a temperature-dependent equivalent of the preformed cluster model PCM ($T \neq 0$). Very recently [1], the DCM approach was exploited to investigate the α-decay chains of $Z = 113$–118 SHN, where the T-dependence was included for the first time via recoil energy of the residual SHN, left after x-neutron emission from the CN. In view of the reasonable agreement of DCM based calculations with the available data on α-decay half-lives, here, in this work, SF half-life of ^{267}Rf has been calculated and compared with the experimental data [2] to test the extent of validity of the DCM formalism to both α-decay and SF processes.

2. Dynamical cluster-decay model

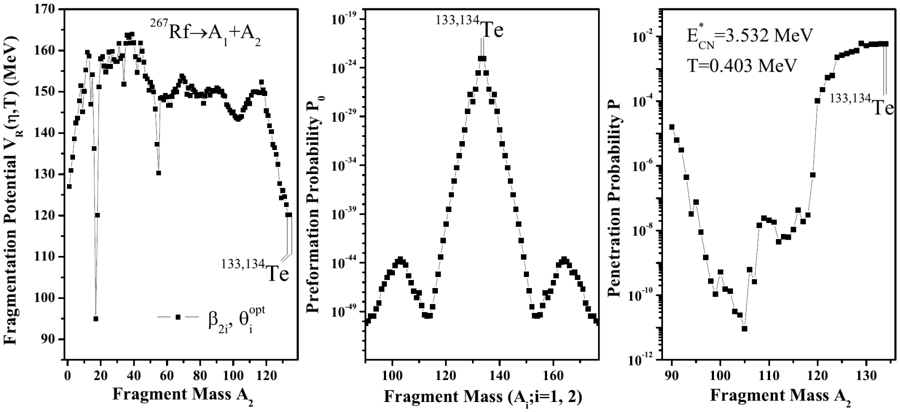
The decay constant λ (related to decay half-life $T_{1/2} = \ln 2/\lambda$) in DCM is the product of three factors: the fragment preformation probability P_0, the barrier impinging frequency ν_0 and the barrier penetration probability P, given by the relation $\lambda = \nu_0 P_0 P$. Here, ν_0 is found to be $\sim 10^{21}$ s^{-1} for the spontaneous decay of ^{267}Rf. The P_0 are the solutions of the stationary Schrödinger equation in mass asymmetry η coordinate

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

which on proper normalization reads as $P_0 = |\psi(\eta(A_i))|^2\sqrt{B_{\eta\eta}}\frac{2}{A_{\mathrm{CN}}}$, with $i = 1{,}2$ and $\nu = 0{,}1{,}2{,}3\ldots$ referring to ground state ($\nu = 0$) and excited state solutions. $B_{\eta\eta}$ is the mass parameter, representing kinetic energy part of the Hamiltonian. Equation (1) is solved at a fixed $R = R_a (= R_1(\alpha_1,T) + R_2(\alpha_2,T) + \Delta R(T))$, the first turning point in the WKB integral for penetrability P. ΔR is the neck-length parameter, which describes the relative separation between the two fragments. The fragmentation potential $V_R(\eta,T)$, at fixed relative separation R, in Eq. (1) is calculated simply as the sum of the binding energies, the Coulomb ($V_{\rm C}$) and proximity ($V_{\rm P}$) potentials, *i.e.*, $V_R(\eta,T) = -\sum_{i=1}^{2} B_i(A_i,Z_i,T)+V_{\rm C}(R,Z_i,\beta_{\lambda i},\theta_i,T)+V_{\rm P}(R,A_i,\beta_{\lambda i},\theta_i,T)$, with details given in Ref. [3]. Since the residual nucleus is considered to be "hot" due to its measured recoil energy $E_{\rm R}$, the temperature T-effects have been incorporated here, with T (in MeV) for the SF of ^{267}Rf nucleus coming into picture via its excitation energy $E^*_{\rm CN} = E_R+Q_{\rm in}$ with $E^*_{\rm CN} = \frac{A}{11}T^2-T$. Here, $Q_{\rm in}$ denotes the Q value of the proceeding α-decaying nucleus, namely, $^{271}106 \rightarrow {}^{267}$Rf + α which gives the Q value via: B.E.(^{271}106) = B.E.(^{267}Rf) + B.E.(α-particle) + Q. Note that Q value in the present analysis has been taken negative, considering that energy is required for SF decay of ^{267}Rf nucleus. Here, B.E.s stand for binding energies calculated within the framework of DCM (see *e.g.* [3]), based on Quantum Mechanical Fragmentation Theory. $E_{\rm R}$ is the recoil energy, and we take $E_{\rm R} = 11.5$ MeV, chosen in reference to the average of the measured [2] $E_{\rm R}$ range (7–16 MeV) for the α-decay chain of the SHN $^{291}116^*$.

3. Calculations and results

Following our recent study [1] on the α-decay chains of SHN, we have investigated the spontaneous fission of ^{267}Rf, appearing as the end product in the measured decay chain of $^{291}116^*$ [2], *i.e.*, to identify the most probable heavy fragment(s) and the corresponding decay half-life within the collective clusterization approach of the DCM. First, we look at the fragmentation potential $V(A_2)$, illustrated in Fig. 1 (a) for ^{267}Rf nucleus, by assuming the fragments with quadrupole deformations β_{2i} alone, having optimum orientations $\theta_i^{\rm opt}$. The decay characteristics clearly show that ^{133}Te is



(a) (b) (c)

Fig. 1. Fragmentation potential $V_R(\eta,T)$ for the spontaneous fissioning ^{267}Rf nucleus using β_2-deformed configuration (a). Panels (b) and (c) represent the same for preformation P_0 and penetration probabilities P.

the most favored fragment (energetically deepest minimum) with the corresponding daughter ^{134}Te for the chosen deformed shapes of nuclei. Note that no data on fragment identification is obtained in experiment [2]. Furthermore, Fig. 1 (b) shows the variation of preformation probability P_0 for the decay of ^{267}Rf which, in turn, accounts for the structure effects in the decay process of a nucleus. Precisely, P_0 measures the probability with which the fragment is formed at the CN stage. The mass distribution of ^{267}Rf comes out to be clearly symmetric for deformed choice of fragments. Apparently, the possible role of nuclear shell closures can be noticed in P_0 by virtue of larger magnitude for symmetric fragment's preformation factor, referring to shell closures around charge $Z = 50$ and neutron number $N = 82$.

As a next step, we have investigated the role of barrier penetrability in Fig. 1 (c) for further verification of most probable fragment. It may be noted that the penetrability for ^{133}Te fragment comes out to be large, the preformation probability is quite small for present choice of deformed configuration. Note that the only parameter of the model is the neck-length ΔR, given in Table I, which decides the entry point of barrier penetration as well as the fragments preformation. The consequences of the above results for P_0 and P are shown explicitly for the half-life time $T_{1/2}$ in Table I for the most favorable fragment in the decay of ^{267}Rf nucleus. Our calculated $T^{\mathrm{SF}}_{1/2}$ agree nicely with experimental data which, in turn, provides a unique opportunity to extend this study to other spontaneously fissioning SHN in order to extract the desired information regarding dynamical behavior of nuclear systems in the extreme mass region of the Periodic Table.

TABLE I

The DCM calculated half-life time and other characteristics for the most favored ^{133}Te light fragment (with corresponding ^{134}Te daughter) emitted in the spontaneous decay of ^{267}Rf nucleus, compared with experimental data.

SF decay	ΔR	Assault	Preformation	Penetration	$T^{\mathrm{SF}}_{(1/2)}$ [h]	
of	[fm]	frequency s^{-1}	probabilty	probability	DCM	(Expt.) [2]
^{267}Rf	0.801	2.61×10^{21}	8.59×10^{-24}	6.02×10^{-3}	1.42	$1.3^{+2.3}_{-0.5}$

4. Summary and conclusions

Summarizing, the dynamics of SF of ^{267}Rf nucleus is studied using the DCM ($\ell = 0$) with quadrupole deformations (β_{2i}) and "optimum" orientations of decay products. The mass fragmentation of ^{267}Rf suggests a clear symmetric distribution, indicating the role of possible shell closure effect(s) of decaying fragment(s). It will be of further interest to extend this study to other SF nuclei of superheavy mass region.

Financial support from the University Grants Commission (UGC), in the form of Maulana Azad National Fellowship, and the Department of Science and Technology (DST), F. No. EMR/2016/000008, is gratefully acknowledged.

REFERENCES

[1] Niyti *et al.*, *Phys. Rev. C* **91**, 054606 (2015).
[2] Yu.Ts. Oganessian *et al.*, *Phys. Rev. C* **74**, 044602 (2006).
[3] B.B. Singh *et al.*, *Phys. Rev. C* **77**, 054613 (2008).