

Exotic decay modes of odd- Z (105–119) superheavy nuclei

N.S. Rajeswari^{1,2} and M. Balasubramaniam^{1,a}

¹ Department of Physics, Bharathiar University, Coimbatore - 641 046, India

² Department of Physics, Avinashilingam Institute for Home Science and Higher Education for Women - University, Coimbatore - 641 043, India

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Abstract. Half-lives of proton emission for proton emitters with $Z = 51$ to 83 are calculated, in the framework of unified fission model with the penetrability calculated using the WKB approximation. For all the ground and isomeric state of the proton, the deformation degree of freedom is included. Calculated half-lives are in good agreement with the experimental ones. Experimentally for a few isotopes, proton and alpha branches are reported. Hence we have calculated the half-lives of alpha decay for these elements. For parent nuclei ^{157}Ta , ^{166}Ir , ^{167}Ir , ^{176}Tl and ^{177}Tl , the alpha decay mode is preferred over the proton emission. Further, the calculations are extended to find half-lives of superheavy element with odd proton number in the range $Z = 105$ to 119, for both proton, alpha and for a few cluster decays. Calculations on superheavy elements reveal that cluster radioactivity has half-lives comparable with proton emissions. It is found that proton emission is the primary competing decay mode with respect to alpha decay for superheavy elements. Among considered clusters, ^{12}C , ^{20}Ne and ^{24}Mg are found to have lowest half-lives among other $N = Z$ clusters and for a few clusters the half-lives are found to be comparable with that of proton emission.

1 Introduction

Proton radioactivity is a process in which a nucleus disintegrates spontaneously by the emission of a proton. Proton drip line represents one of the fundamental limits of nuclear existence and nuclei in this region have excess of protons and undergo spontaneous proton emission towards stability. The inverse process of proton radioactivity, called rapid proton capture, plays an inevitable role in nuclear astrophysics. Structural information about the parent and the daughter of the drip line nuclei are provided by proton decay studies. One of the highlighting features about proton emitters is the possibility to extract the parent angular momentum by analysing the experimental proton Q -values and their partial half-lives. This is based on the strong dependence of proton half-lives on angular momentum and energy. For the proton emission to occur, the Q -value must be positive and the proton must tunnel the potential energy barrier provided by the daughter nucleus.

Experimentally proton emission was first observed from proton unstable isomer ^{53m}Co by Jackson *et al.* [1] in 1970 and this was confirmed by Cerny *et al.* [2] in the same year. With the advent of improved experimental facilities

and radioactive beams, proton emission from ground and isomeric states has been identified between $Z = 51$ and 83 [3–10]. Extensive theoretical attempts were made to study this exotic process [11–21]. By extending the model of alpha and exotic decay, using the Woods-Saxon type potential, for proton emission, seven ground-state proton emitters were studied by Buck *et al.* [11]. A detailed comparison between different methods such as Distorted Wave Born Approximation (DWBA), two-potential approach and simple description of barrier penetration were analysed by Aberg *et al.* [12]. Within the liquid-drop model, using the WKB approximation, proton half-lives are calculated in refs. [13–15].

Using the unified fission model (UFM), modified from the preformed cluster model (PCM) of Gupta and collaborators [16], one of us has reported half-lives of spherical proton emitters and alpha decay as a competing mode for proton emission [17]. For the same data from [17], Basu *et al.* [18] have calculated half-lives using a density-dependent M3Y effective interaction potential based on nuclear matter calculations. A simple formula for the half-life was given in [19], similar to the Geiger-Nuttall rule for proton emission. The semi-empirical one-parameter model was employed to calculate the half-lives of proton emitters [20]. Recently, proton formation probability, extracted from the experimental data, is used to explain proton

^a e-mail: m.balou@gmail.com

radioactivity [21]. Half-lives of proton radioactivity were calculated by Routray *et al.* [22] within the WKB penetrability using the proton-nucleus interaction potential obtained from folding the density of the residual daughter nucleus with a finite-range effective nucleon-nucleon interaction having a single Yukawa term in the finite range part. Later Routray *et al.* [23] used different Skyrme sets in the framework of the semiclassical WKB method to calculate proton half-lives.

Sahu *et al.* [24] have used the microscopic Michigan-3-Yukawa (M3Y) and relativistic mean field-3-Yukawa (R3Y) nucleon-nucleus interaction potential by including the angular momentum potential for the half-lives of proton emitters. Alpha decay is the primary decay mode for heavy and superheavy nuclei. There are numerous studies on the alpha decay of superheavy elements using different formalisms [25–36]. Poenaru *et al.* [37,38] predicted cluster radioactivity of superheavy elements for heavy clusters with $Z > 28$. Poenaru *et al.* [39] calculated half-lives of even-even isotopes of proton-rich cluster emitters such as Ba, Ce, Nd, Sm, Gd and Dy for clusters ^{12}C , ^{16}O , ^{20}Ne , ^{24}Mg and ^{28}Si , within analytical super-asymmetric fission model (ASAF) and discussed the branching ratio of these cluster emissions relative to α -decay.

In the present work, we have calculated the half-lives of proton and alpha emission for known proton emitters from ground and isomeric state and proton, alpha and cluster emissions of odd- Z superheavy nuclei with $Z = 105$ to 119. The calculations are done in the framework of the unified fission model, modified from PCM, which accounts for the preformation probability as the penetrability of overlapping potential, as interpreted by Poenaru and Greiner [40]. The methodology is briefly described in the following section and the results and discussion are presented in sect. 3.

2 The methodology

The potential for the overlapping region is considered as a second-order polynomial in terms of the relative separation R and, for the post-touching region, it is the sum of Coulomb, proximity and angular momentum potentials. Also, the potentials are considered to be dependent on the deformations $\beta_{\lambda i}$ ($\lambda = 2$ quadrupole deformations only taken into account and $i = 1, 2$) of the fragments and the orientation of the nucleus is considered to be $0(\theta = 0)$. The potential for the overlapping region is given as

$$V_{ov}(R) = a_1 R + a_2 R^2 \quad \text{for } R_0 \leq R \leq R_t, \quad (1)$$

where the constants a_1 and a_2 are calculated using the boundary conditions, $V_{ov}(R) = Q$ at $R = R_0$ and, at $R = R_t$, the potential of overlapping is equal to V_{nov} . V_{nov} is the potential for the post-scission region, which is defined as

$$V_{nov}(R) = V_C + V_P + V_\ell, \quad (2)$$

at $R = R_t$, with R_0 as the parent nucleus radius and R_t is the relative separation at the touching configuration, given

as $R_t = C_{01} + C_{02}$. Calculations are carried out with

$$R_i(\alpha_i) = R_{0i} \left(1 + \sum \beta_{\lambda i} Y_\lambda^{(0)} \right) \text{ fm}, \quad (3)$$

for the effective sharp radius given by

$$R_{0i} = 1.28 A_i^{\frac{1}{3}} - 0.76 + 0.8/A_i^{\frac{1}{3}} \text{ fm} \quad (4)$$

and the corresponding central radius as

$$C_{0i} = R_{0i} \left(1 - \frac{b^2}{R_{0i}^2} \right) \text{ fm}, \quad (5)$$

C_{0i} ($i = 0, 1, 2$) are the Süssman's central radii, respectively, for the parent, daughter nuclei and particle emitted. Here this formalism is applied for proton, alpha and a few cluster emissions. V_C , V_P and V_ℓ are, respectively, the Coulomb, proximity and centrifugal potentials defined below.

The deformation-dependent Coulomb potential [41] is given as

$$V_C = \frac{Z_1 Z_2 e^2}{R} + 3 Z_1 Z_2 e^2 \sum_{\lambda, i=1,2} \frac{1}{2\lambda + 1} \frac{R_i^{\lambda}(\alpha_i)}{R_i^{\lambda+1}} Y_\lambda^{(0)} \left[\beta_{\lambda i} + \frac{4}{7} \beta_{\lambda i}^2 Y_\lambda^{(0)} \right], \quad (6)$$

where Z_1 and Z_2 are the charge numbers of the fragments (daughter and emitted particle as the case may be proton or alpha or cluster) and $e^2 = 1.44 \text{ MeV fm}$. Quadrupole deformation (β_{2i} , $i=0, 1, 2$) values are taken from ref. [42]. The centrifugal potential is given as

$$V_\ell = \frac{\hbar^2 \ell(\ell + 1)}{2I}, \quad (7)$$

with the moment of inertia taken in the complete non-sticking limit as

$$I = I_{NS} = \mu R^2. \quad (8)$$

Here $\mu = [A_1 A_2 / (A_1 + A_2)] m = \frac{1}{4} A m (1 - q^2)$ as the reduced mass with m as the nucleon mass. The nuclear part of the interaction potential, proximity potential of Blocki *et al.* [43] is given by

$$V_P = 4\pi \bar{R} \gamma b^2 \Phi(\xi), \quad (9)$$

\bar{R} is the mean curvature radius of the reaction partners, characterising the gap, which, for deformed nuclei, is given by

$$\bar{R} = \frac{C_{01} C_{02}}{C_{01} + C_{02}} \text{ fm}, \quad (10)$$

where $\Phi(\xi)$ is the universal function of proximity potential, which depends only on the distance between two nuclei and is independent of the charge numbers of the two nuclei, given as

$$\Phi(\xi) = \begin{cases} -\frac{1}{2}(\xi - 2.54)^2 - 0.0852(\xi - 2.54)^3, & \xi \leq 1.251 \\ -3.437 \exp\left(-\frac{\xi}{0.75}\right), & \xi \geq 1.251. \end{cases} \quad (11)$$

Here, $\xi = s/b$, $s = R - C_t$, R being the separation distance between the fragments and $C_t = C_{01} + C_{02}$. This function is defined for negative (the overlapping region), zero (touching configuration) and positive values of s . $b = 0.99$ fm is the diffuseness of the nuclear surface. γ is the specific nuclear surface energy co-efficient, given by

$$\gamma = \gamma_0 \left[1 - k_s \left(\frac{N - Z}{A} \right)^2 \right] \text{ MeV fm}^{-2}. \quad (12)$$

In the above formula, γ_0 is the surface energy constant and k_s is the surface-asymmetry constant. Both these quantities were parametrised by Myers and Swiatecki [44] as, $\gamma_0 = 0.9517$ MeV/fm² and $k_s = 1.7826$. The decay half-life $T_{1/2}$ of the parent nucleus (A, Z) into a daughter (A_d, Z_d) and a particle (proton/alpha/cluster emissions) is given by

$$T_{1/2} = \frac{\ln 2}{\lambda_d}. \quad (13)$$

The decay constant in unified fission model is defined as,

$$\lambda_d = \nu_0 P \quad (14)$$

Here the total penetration probability is written as the product of penetrability of the overlapping region and the post-touching region, given by

$$P = P_{ov} P_{nov} = \exp(-(K_{ov} + K_{nov})), \quad (15)$$

where K_{ov} and K_{nov} are the action integrals along the fission path in the overlapping and non-overlapping regions, given by

$$K_{ov} + K_{nov} = \frac{2}{\hbar} \left[\int_{R_0}^{R_t} \{2\mu[V_{ov}(R) - Q]\}^{1/2} dR \right] + \frac{2}{\hbar} \left[\int_{R_t}^{R_b} \{2\mu[V_{nov}(R) - Q]\}^{1/2} dR \right]. \quad (16)$$

Here R_0 and R_b are the first and second turning points, respectively. The second turning point is calculated from the condition $V(R_b) = Q$. The assault frequency in eq. (14) is given by

$$\nu_0 = \frac{1}{2R_{0i}(\alpha_i)} \sqrt{\frac{2E_2}{\mu}}, \quad (17)$$

which is the frequency with which the particle hits the barrier and $R_{0i}(\alpha_i)$ is the radius of the deformed parent nucleus and

$$E_2 = \frac{1}{2} \mu v^2 \quad (18)$$

is the kinetic energy of the particle (proton/ α /cluster) inside the nucleus.

The branching ratio of proton with respect to α emission is defined as

$$BR = \frac{\lambda_p}{\lambda_\alpha}. \quad (19)$$

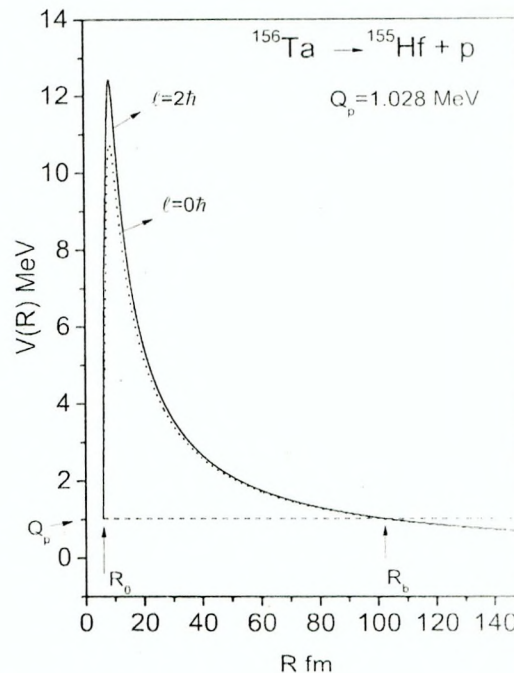


Fig. 1. Potential barrier for the proton emission from the parent nucleus ^{156}Ta . The solid line corresponds to the angular momentum $\ell = 2\hbar$ and the dotted line corresponds to the angular momentum $\ell = 0\hbar$. Q_p -value is labelled.

Similarly, the branching ratio of cluster emission relative to alpha or proton decay is given by

$$BR = \frac{\lambda_{\text{Cluster}}}{\lambda_\alpha}; \quad BR = \frac{\lambda_{\text{Cluster}}}{\lambda_p}. \quad (20)$$

where λ_p is the calculated decay constant for proton emission, λ_α is the calculated decay constant for alpha emission and λ_{Cluster} is the calculated decay constant for cluster emission.

3 Results and discussion

For the proton emission, the valence proton must tunnel through the potential barrier consisting of the Coulomb, centrifugal and proximity potentials. The contribution from the centrifugal barrier is high, hence the proton half-life depends on the angular momentum. Figure 1 shows the potential barrier for the proton emission of the parent nucleus ^{156}Ta , for the angular momentum $\ell = 2\hbar$ and $0\hbar$, indicating the increase in the barrier as ℓ increases. Half-lives of 43 proton emitters, in their ground and isomeric states, are calculated for the data taken from refs. [19, 20], with the experimental values of angular momentum ℓ and Q_p from the same. Of the different proton emitters as well as all the superheavy nuclei considered, some of the parent nuclei are deformed. However in the present calculations the deformation degree of freedom is considered for all the known proton emitters as well as for superheavy nuclei. Calculated half-lives are listed in table 1

Table 1. Decimal logarithmic half-lives of proton emitters with $Z = 51$ to 83 . The first column indicates the parent nucleus. The second column gives angular momentum values for proton emission and the third column gives the experimental Q_p -values. Exp.(p) and Cal.(p) indicates the experimental [19, 20] and calculated logarithmic half-lives for proton emission. Cal.(α) indicates the calculated logarithmic half-lives for alpha emission. Exp.(α) gives experimental half-lives for a few cases, taken from refs. [16, 7, 8]. The last column lists the branching ratio for proton emission relative to alpha calculated using decay constants (λ_p/λ_α).

Parent nucleus	ℓ (\hbar)	Q_p (MeV)	$\log_{10} T_{1/2}$ ($T_{1/2}$ in s)				Cal.BR(λ_p/λ_α)
			Exp.(p)	Cal.(p)	Cal.(α)	Exp.(α)	
^{105}Sb	2	0.491	2.049	2.554	2.688 ^(a)	–	1.36
^{109}I	2	0.829	–3.987	–4.105	–2.141 ^(a)	–	91.97
^{112}Cs	2	0.824	–3.301	–3.397	–1.595 ^(a)	–	63.29
^{113}Cs	2	0.978	–4.777	–5.539	–0.260 ^(a)	–	1.89×10^5
^{117}La	2	0.823	–1.602	–2.822	2.271 ^(a)	–	1.24×10^5
^{121}Pr	2	0.900	–2.000	–3.355	3.078 ^(a)	–	2.71×10^6
^{130}Eu	2	1.028	–3.046	–3.849	3.117 ^(a)	–	9.25×10^6
^{131}Eu	2	0.951	–1.575	–2.808	2.683 ^(a)	–	3.09×10^6
^{135}Tb	3	1.188	–3.027	–4.256	0.904 ^(a)	–	1.45×10^7
^{140}Ho	3	1.106	–2.222	–2.654	0.679 ^(a)	–	2.10×10^3
^{141}Ho	3	1.190	–2.387	–3.630	1.177 ^(a)	–	6.41×10^1
$^{141}\text{Ho}^*$	0	1.256	–5.180	–6.094	–	–	–
^{145}Tm	5	1.753	–5.409	–4.817	1.452 ^(a)	–	1.86×10^6
^{146}Tm	5	1.210	–1.276	0.618	3.356 ^(a)	–	5.47×10^2
$^{146}\text{Tm}^*$	5	1.148	–0.456	1.346	–	–	–
^{147}Tm	5	1.071	0.591	2.346	4.088 ^(a)	–	55.18
$^{147}\text{Tm}^*$	2	1.139	–3.444	–2.204	–	–	–
^{150}Lu	5	1.283	–1.180	0.254	11.643	–	2.45×10^{11}
$^{150}\text{Lu}^*$	2	1.317	–4.523	–3.645	–	–	–
^{151}Lu	5	1.255	–0.896	0.510	14.791	–	1.91×10^{11}
$^{151}\text{Lu}^*$	2	1.332	–4.796	–3.828	–	–	–
^{155}Ta	5	1.791	–4.921	–4.215	13.417	–	4.29×10^{17}
^{156}Ta	2	1.028	–0.620	0.191	4.500	–	2.03×10^1
$^{156}\text{Ta}^*$	5	1.130	0.949	2.155	–	–	–
^{157}Ta	0	0.947	–0.523	0.321	–2.311 ^(a)	< –2.28	2.33×10^{-13}
^{159}Re	5	1.836	–4.678	–4.148	–3.104 ^(a)	–	11.06
^{160}Re	2	1.284	–3.046	–2.826	–2.568	–2.060	1.81
^{161}Re	0	1.214	–3.432	–2.943	–1.515 ^(a)	–1.820	26.80
$^{161}\text{Re}^*$	5	1.338	–0.488	–0.284	–	–	–
^{164}Ir	5	1.844	–3.959	–4.045	–3.150 ^(a)	–	7.84
^{165}Ir	5	1.733	–3.469	–3.346	–2.735 ^(a)	–	4.09
^{166}Ir	2	1.168	–0.824	–0.932	–2.503 ^(a)	> –2.30	2.68×10^{-2}
$^{166}\text{Ir}^*$	5	1.340	–0.076	0.149	–	–	–
^{167}Ir	0	1.086	–0.959	–0.700	–1.768 ^(a)	>= –1.29	8.54×10^{-2}
$^{167}\text{Ir}^*$	5	1.261	0.875	0.996	–	–	–
^{170}Au	2	1.497	–3.444	–4.014	–2.891 ^(a)	–	13.30
$^{170}\text{Au}^*$	5	1.767	–3.076	–3.257	–	–	–
^{171}Au	0	1.469	–4.770	–4.423	–2.675 ^(a)	–	56.08
$^{171}\text{Au}^*$	5	1.718	–2.654	–2.453	–	–	–
^{176}Tl	0	1.268	–2.284	–1.372	–2.524	–	0.07
^{177}Tl	0	1.180	–1.174	–0.252	–0.990	–1.745	0.18
$^{177}\text{Tl}^*$	5	1.986	–3.347	–3.612	–	–	–
^{185}Bi	0	1.624	–4.229	–4.671	–4.142	–4.301	3.37

(a) Calculations for these cases are done using shifted touching point, explained in the text.

and the values are in good agreement with the experimental values. The isomeric state of the nuclei is indicated by the asterisk symbol (*) in the parent nuclei. Standard deviation of the calculated half-lives for proton emission, from the experimental values for these 43 cases is found to be 0.896. A better matching between calculated and experimental half-lives is found for a few systems, such as ^{109}I , ^{112}Cs , ^{159}Re , ^{160}Re , ^{161}Re , ^{164}Ir , ^{165}Ir , ^{166}Ir , $^{166}\text{Ir}^*$, ^{170}Au , $^{170}\text{Au}^*$, ^{171}Au , $^{171}\text{Au}^*$, $^{177}\text{Tl}^*$ and ^{185}Bi . Logarithmic half-life values of proton emission varies between -6.094 to 2.554 . The preformation factor P_{ov} of the proton emission calculated using eq. (15), which is the penetrability of the overlapping potential, for these 43 proton emitters varies from 0.119 to 0.895.

Proton and alpha branches were well established for a few ground and isomeric states of proton drip line nuclei. Hence we have calculated half-lives for alpha emission for the same elements listed in table 1, in their ground state. Q -values for alpha decay are found using the recently updated table of masses of Wang *et al.* [45]. Calculated half-lives are listed in table 1. Out of 43 cases, only 31 cases are considered for the alpha decay, since the ground-state decay alone is taken into consideration. Half-lives for the alpha decay of the proton emitters resulted only for 8 cases out of 31 cases, because the potential is less than the Q -value for other 23 cases. For these 23 cases which are superscripted with an “(a)” in table 1, we have extended the touching point by 0.5 fm uniformly in order to make the potential greater than the Q -value and also it is continuous with the potential of the post-touching region. Experimental decimal logarithmic half-lives are listed for a few systems for the alpha decay taken from a compilation of Duarte *et al.* [46] and the experimental work of Poli *et al.* [7, 8]. For nuclei ^{157}Ta , ^{160}Re , ^{161}Re , ^{166}Ir , ^{167}Ir and ^{185}Bi , half-lives match with the experimental values. The preformation probability (P_{ov}) of the proton is found to be larger than the alpha emission except for ^{160}Re . It is understood, from the results of half-lives and the branching ratio (BR) calculated using eq. (19) of proton emission relative to alpha, proton emission is preferred by the proton emitters in the range $Z = 51$ to 73. For the parent nucleus ^{155}Ta , BR is found to be very high of the order of 10^{17} , implies that one alpha particle will be observed in the background of 10^{17} events of proton. For the parent nuclei ^{166}Ir , ^{167}Ir , ^{176}Tl and ^{176}Tl , the branching ratio are found to be 0.0268, 0.0854, 0.0704 and 0.183, respectively, indicates the preference for alpha decay over proton emission. Minimum value of BR is found to be 2.335×10^{-3} for ^{157}Ta indicates the preference of alpha decay over proton emission. For the known proton emitters, the Q -value for cluster emission is found to be negative. Hence cluster emission in the range $Z = 51$ to 83, may not be a competing decay mode with proton emission. However cluster emission is considered for the superheavy nuclei, for which the Q -value is positive.

Extensive studies were made on the alpha decay of experimentally synthesised superheavy elements and there were some attempts [37, 38] to predict the cluster decay of the SHEs. Hence we have extended our study to find the alpha and proton decay half-lives of odd- Z superheavy

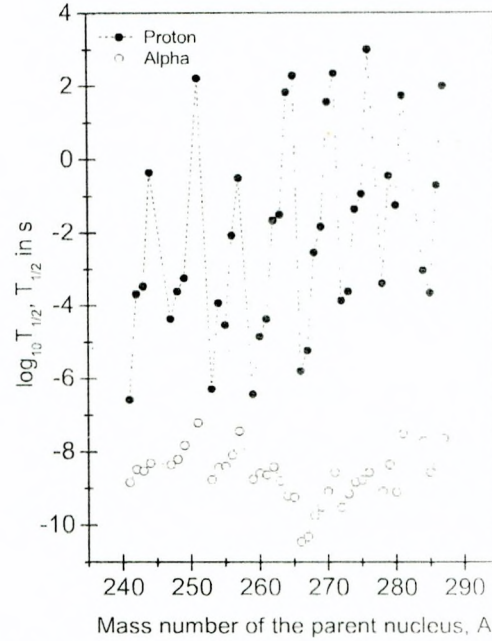


Fig. 2. Decimal logarithmic half-lives of the superheavy elements for proton emission (solid circle with dashed line) and alpha emission (open circle with dotted line), for nuclei with odd proton number with $Z = 105$ to 119.

nuclei in the mass region $A = 241$ to 287. Figure 2 represents the decimal logarithmic half-lives of 39 superheavy elements with $Z = 105$ to 119 for proton emission and alpha decay, for ground state. Half-lives for alpha emission resulted only for 9 cases, since the total potential is less than the Q -value. Hence we have extended the touching point by 0.2 fm, uniformly for other 30 cases and the logarithmic half-lives are presented in fig. 2. For alpha decay the half-lives are found to be in the range of nano seconds to 10^{-11} s, whereas for proton emission the calculated half-lives are higher than alpha emission and varies from 2.65×10^{-7} s to 1.017×10^3 s. Low values of half-lives mean the higher branching ratio for alpha emission, which confirms the preference for alpha decay over proton emission. Branching ratio calculated for proton emission relative to alpha decay has a minimum value of 2.718×10^{-12} and a maximum value of 5.6×10^{-3} , which implies nearly one proton event will be observed among 10^{12} and 10^3 events of alpha decay, respectively.

The cluster decay in the heavy-mass region is well established for the clusters such as ^{14}C , $^{22-26}\text{Ne}$, $^{28-30}\text{Mg}$, $^{32,34}\text{Si}$. Our model is extended to the superheavy region to study the cluster decay also. For the cluster emission of superheavy nuclei, only even-even clusters such as C, Ne, Mg, Si, Ar and Ca are considered. Half-life values greater than 10^{30} are not taken into account. Hence the calculation results in clusters $^{12,14}\text{C}$, $^{20,22,24}\text{Ne}$, $^{24,26,28}\text{Mg}$, $^{28,30}\text{Si}$, $^{32,34}\text{Si}$, $^{36,38,40,42,44}\text{Ar}$ and $^{40,42,44,46,48}\text{Ca}$. Q -values for the cluster decays are calculated using the updated mass table of Wang *et al.* [45] and we have used the theoretical masses of Moller *et al.* [42], wherever masses are not available in Wang *et al.*

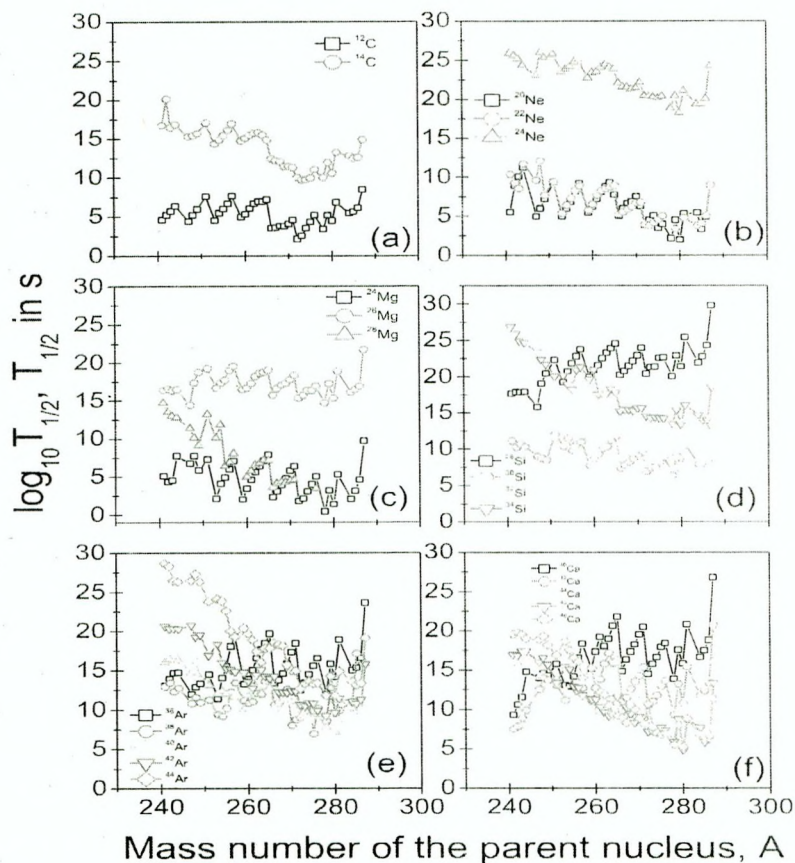


Fig. 3. Decimal logarithmic half-lives of the superheavy elements for isotopes of carbon, neon, magnesium, silicon, argon and calcium with the mass number of the parent nucleus.

Figure 3 shows the decimal logarithmic half-lives for the decay of clusters of C, Ne, Mg, Si, Ar and Ca for the parent nuclei with $Z = 105$ to 119 , in separate panels. Firstly we have started with the clusters $Z = N$, in each of the clusters considered. Then we moved towards $Z \neq N$. In fig. 3(a), half-lives for two isotopes of carbon are presented. Among the two isotopes, for the emission of ^{12}C , the half-lives are found to be less than half-lives of ^{14}C , for all the parent nuclei. For each isotopic chain of $Z = 105$ to 119 , in the case of ^{12}C , as mass number A increases, half-life value increases, indicating the preference for cluster by the low- Z parent isotope. This trend is not followed in the case of ^{14}C . Amongst the considered clusters of neon, ^{20}Ne competes with ^{22}Ne as shown in fig. 3(b), whereas ^{24}Ne is less preferred, when compared with the other two clusters of neon. Among magnesium clusters, ^{24}Mg has got the lowest half-life value and it is the most preferred cluster, especially in heavy mass region of $A > 250$, as shown in fig. 3(c). Even though ^{26}Mg has the highest half-lives and for a few parents $A = 260$ to 271 , ^{28}Mg competes with the cluster ^{24}Mg .

In fig. 3(d), logarithmic half-lives of 4 isotopes of silicon are drawn. ^{30}Si has got the lowest half-life values and has the highest preference. In the mass region $A > 250$ ^{32}Si competes with ^{30}Si . Highest half-life values are found for

^{34}Si . Five argon clusters have logarithmic half-lives less than 10^{30} , as displayed in fig. 3(e). Till $A = 255$, ^{38}Ar has the lowest half-life. Beyond that, $A = 255$ to 287 , ^{40}Ar as well as ^{42}Ar compete with ^{38}Ar . ^{44}Ar has got the highest half-life for the range $A = 241$ to 262 and, for $A > 262$, ^{36}Ar has high half-life values. Half-life values of ^{42}Ar lie between ^{38}Ar and ^{44}Ar . Among the argon clusters, ^{38}Ar is preferred.

Figure 3(f) represents the half-lives of calcium clusters with $A_2 = 40, 42, 44, 46, 48$. ^{40}Ca has the highest half-life with $Z = N$, whereas ^{12}C is having the lowest half-life with $Z = N$. This implies that at low mass numbers, clusters with $Z = N$ are preferred, whereas the mass number of the cluster is increased, the preference is shifted towards, $Z \neq N$ clusters. Among the calcium isotopes, for $Z = 105$ and 107 , ^{42}Ca and ^{44}Ca are competing. For $A > 264$, ^{48}Ca has the lowest logarithmic half-life of the order of 10^5 . Among all the clusters considered logarithmic half-lives of ^{12}C ranges from 2.18 to 8.5135 ; for ^{20}Ne , it ranges between 1.97 to 11.223 and for the cluster ^{24}Mg it lies between 0.45 to 9.698 . ^{24}Mg has the lowest logarithmic half-life of 0.45 for the parent nucleus $^{278}117$. It is to be mentioned here that the preference for $N = Z$ cluster is noted for those clusters which has a low Z value. As we move towards heavier clusters, probability for $N \neq Z$

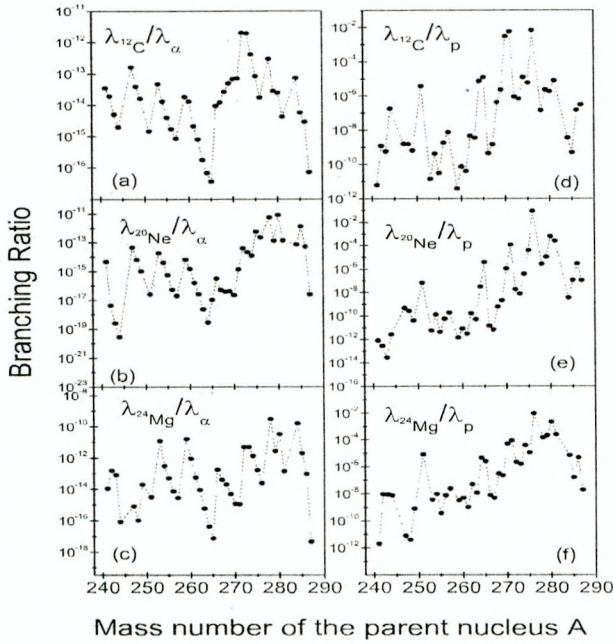


Fig. 4. Branching ratio of the superheavy elements with odd proton number $Z = 105$ to 119 , for ^{12}C , ^{20}Ne and ^{24}Mg emission with respect to alpha emission panels (a), (b) and (c), respectively, and ^{12}C , ^{20}Ne and ^{24}Mg emission with respect to proton emission panels (d), (e) and (f), respectively.

clusters is found to be more when compared to $N = Z$ clusters. ^{12}C among carbon isotopes, ^{20}Ne in neon and ^{24}Mg in magnesium are the preferred clusters with $N = Z$ case; whereas ^{26}Mg in magnesium, ^{30}Si in silicon, ^{38}Ar and ^{40}Ar among argon, and ^{42}Ca , ^{44}Ca and ^{48}Ca among calcium clusters are preferred for the $N \neq Z$ case.

We have calculated the BR of ^{12}C , ^{20}Ne and ^{24}Mg relative to alpha as well as for proton emissions which are presented in fig. 4. In fig. 4, panels (a), (b) and (c) present the branching ratio of ^{12}C , ^{20}Ne and ^{24}Mg relative to alpha, and panels (d), (e) and (f) represent the branching ratio of ^{12}C , ^{20}Ne and ^{24}Mg relative to proton, respectively. The BR for ^{12}C emission relative to alpha, in fig. 4(a) varies from 10^{-17} to 10^{-12} , indicating that one event of ^{12}C emission can be observed in the background of 10^{17} to 10^{12} alpha particles. In the case of BR of ^{12}C emission relative to proton, the values are found to lie between 10^{-12} to 10^{-3} , implies the increase in preference for ^{12}C among the proton background, as represented in fig. 4(d). The branching ratio for ^{20}Ne with respect to alpha emission is found to lie between 10^{-20} and 10^{-12} and, with respect to the proton emission, is found to lie between 10^{-14} and 10^{-2} . BR of 0.088 is observed for the element $^{276}115$ indicates the increase in the preference for ^{20}Ne among proton background. In the case of ^{24}Mg , BR relative alpha decay varies between 10^{-18} to 10^{-10} and with respect to the proton emission is found to be 10^{-12} and 10^{-3} . Hence it is predicted that ^{12}C , ^{20}Ne and ^{24}Mg clusters can compete with proton emission among $N = Z$ clusters for the odd- Z superheavy nuclei $Z = 105$ to 119 .

4 Summary

Half-lives of 43 proton emitters of proton drip line, with $Z = 51$ to 83 , for ground and isomeric states of deformed nuclei for the emission of proton are calculated within the frame work of unified fission model, modified from PCM of Gupta and collaborators. Calculated values are in good agreement with the experimental values for proton emission. It is clear from experiments that alpha and proton branches are reported for a few nuclei. Hence half lives for α decay are also calculated for 31 cases of proton emitters in their ground state. For the parent nuclei ^{172}Ta , ^{166}Ir , ^{167}Ir , ^{176}Tl and ^{176}Tl , alpha decay is preferred. Since there is a fair agreement between the calculated and experimental half-lives for proton emission and a few alpha emission, we have extended our calculations to find half-lives for both alpha and proton emissions for the superheavy nuclei with odd- Z , from 105 to 119 with the parent mass number in the range $A = 241$ to 287 . Calculation reveals that alpha emission is found to be the primary decay mode for superheavy nuclei. We have extended our study to find half-lives of a few even-even clusters such as C, Ne, Mg, Si, Ar and Ca. Amongst the isotopes considered ^{12}C , ^{20}Ne and ^{24}Mg has the lowest half-life and are the highest preferred clusters with $N = Z$ and as we move towards heavier clusters only clusters with $N \neq Z$ are preferred. It is understood from the branching ratio of these clusters with respect to alpha and proton emission, that emission of clusters ^{12}C , ^{20}Ne and ^{24}Mg can be considered as a competing decay mode for proton emission. However alpha decay mode is the preferred decay mode for odd Z superheavy nuclei in the range $Z = 105$ to 119 .

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