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Comparison between Cluster Decays, Halo Emissions, Alpha Decay and Spontaneous Fission from $^{290-320}$122 Superheavy Nuclei

K. Prathapan[1], K. P. Anjali[2], R. K. Biju[3*]

Research Scholar[1, 2], Assistant Professor[3]

Department of Physics

Govt. Brennan College, Thalassery,-670106, India[1, 2],

Pazhassi Raja NSS College, Mattanur- 670702, India[3]

***Corresponding Author's Email id:** - bijurkn@gmail.com[3*]*

Abstract

A comparative study on the most probable light cluster decay, halo emission and alpha decay from $^{290-322}$122 even-even parent nuclei were made using the Coulomb and Proximity Model for Deformed Nuclei (CPPMDN), Unified formula (UD), Universal Decay Law (UDL) and formula of Horoi et al. The results obtained using CPPMDN, UDL and the Horoi formula are in good agreement, but the UD predict much lower $T_{1/2}$ values than other models except for alpha decay. All the four models predict that the most probable light clusters from each isotope family with $Z \leq 10$ are ^{8}Be, ^{11}B, ^{12,14}C, ^{15}N, ^{18}O, ^{23}F and ^{24}Ne. The neutron halo nuclei ^{15}C and ^{24}F are also possible to emit from the parents. A study on the spontaneous fission (SF) half-life is also performed using the formula of KPS (2010) and modified formula of KPS (2017). The comparative study between the alpha emission, spontaneous fission, cluster decay and halo emission shows that the parent nuclei $^{290-312}$112 decay through alpha emission and for the parents $^{314-322}$122, SF is dominant. However, the parents $^{290-308,320}$122 are cluster emitters and $^{310-318}$122 are both cluster and halo emitters with a decay half-life less than the experimental limit of 10^{30} seconds. The neutron shell closure at neutron number 184 is evident from the plot of $\log_{10} T_{1/2}$ verses the neutron number of parents.

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***Keywords**: - Cluster Radioactivity, Halo Nuclei, Deformation.*

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INTRODUCTION

The computation of half-lives of alpha decay, cluster decay, spontaneous fission etc. is a powerful tool in the prediction of stability of various isotopes of elements in the heavy and super heavy region. Heavy and superheavy elements decay through various processes such as spontaneous fission, alpha decay and cluster radioactivity. Nuclei heavier than alpha particle are generally known as clusters. The cluster radioactivity was predicted in 1980 [1] by Sandulescu et al., based on quantum mechanical fragmentation theory and was experimentally confirmed in 1984 by H J Rose and G A Jones [2] in the natural decay of ^{223}Ra which emits ^{14}C cluster. Followed by this, the emission of many clusters such as ^{20}O, ^{24,26}Ne, ^{23}F, ^{28,30}Mg, ^{32}Si etc., from heavy elements were discovered experimentally [3]. A new class of clusters were identified in 1985, when I Tanihata et al., discovered the large nuclear matter distribution of ^{11}Li [4], through the measurement of interaction cross section. This discovery presented a new challenging field for the nuclear scientists to investigate the exotic properties of neutron rich nuclei near the neutron drip line. The new phenomenon was named as halo. The halo manifests in the form of a large nuclear deformation or as a long tail in the nuclear matter distribution as in the case of ^{11}Li. In a halo nucleus, the last one or two nucleons must have a separation energy less than 1MeV. Due to the weak binding force, the last nucleon exhibits a kind of quantum mechanical tunneling and reaches the classically forbidden region forming a low-density region around the core [5]. In such nuclei, the last nucleon spends most of the time beyond the nuclear attractive potential, thereby making the matter radius much larger than that of a normal nucleus [6,7]. Since from the discovery, the halo phenomenon became interesting and challenging area of study for my researchers [8-13]. A halo can be either a proton halo or a neutron halo [7].

To describe cluster decay various alpha-like and fission-like theories were proposed [14]. The relativistic mean filed (RMF) calculations are widely used for estimating the binding energy, rms matter radius and other ground state properties of spherical and deformed nuclei [15,16, 17, 18]. Theoretical models such as Hartree Bogoliubov model with and without Fock term, Relativistic mean field modal with Hartree approximation [15], deformed relativistic Hartree Bogoliubov (DRHB) theory [19] are useful in describing the structure and properties of halo nuclei. Another interesting feature of the nuclei

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near the drip-line region, especially the halo nuclei, is the emergence of new magic numbers resulting from the dynamic effects of nucleon-nucleon interaction. Many researchers predicted new neutron magic numbers 152, 162, 172, 178 and 184 as well as proton magic numbers 100, 104, 108, 120, 126 and 164 using relativistic mean field calculations [20,21,22] and by considering the stability of the parent nuclei against alpha decay [23].

Apart from ^{11}Li the halo structure was confirmed in many nuclei such as ^{6}He, ^{9}Be, ^{11}Be, ^{14}Be, ^{14}C, ^{19}C etc. [7]. Other predicted neutron halo nuclei include ^{22}N, ^{19}O, ^{23}O, ^{24}F, ^{26}F, ^{27}F, ^{29}F, ^{29}Ne etc. [7, 13]. In 2009 T Nakamura et al. predicted the halo structure of ^{31}Ne by measuring the reaction cross sections for single-neutron removal from the very neutron-rich nucleus ^{31}Ne on lead and carbon targets at an energy of 230 MeV per nucleon using the RIBF facility at RIKEN [24]. In2014, M.Takechi et. al. confirmed the existence of the so far heaviest halo in ^{37}Mg through the measurement of reaction cross-section [25]. Neutron halo can be either a 1-neitron halo or a 2-neutron halo. For a 1-n halo, the 1-n separation energy is the lowest and for a 2-n halo, 2-n separation energy will be the lowest. Since a halo-nuclei is heavier than the alpha particle, they are considered as clusters and their formation from decay of elements from heavy and superheavy region are considered as cluster radioactivity. For the study of cluster radioactivity many theoretical and empirical models are available. Some of them are Preformed Cluster Model (PCM), Analytical Super Symmetric Fission Model (ASSFM), Coulomb and Proximity Potential Model (CPPM), Single Line of Universal Curve (UNIV), Universal Decay Law (UDL) etc. [26,27,28, 29, 30].

In the present work we havemade a comparative study between the most probable cluster emissions, neutron halo emissions, alpha decay and spontaneous decay from even-even isotopes of Z = 122 superheavy nuclei. The study of nuclear reactions involving elements in the super heavy region gained much attention after the new developments in the hot fusion reactions. Superheavy elements with Z = 112 – 118 were successfully synthesized through various fusion reactions with ^{48}Ca beam on various actinide targets through hot fusion reactions [31, 32] The experimentally measured alpha decay half-lives of these elements are found to be in agreement with the theoretical predictions made by Gambhir et al. based on

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relativistic mean field calculations [33]. Attempts were made to produce elements with Z = 119 and 120 through the hot fusion of ^{244}Pu and ^{58}Fe [34]. In 2016, K P Santhosh et al studied the feasibility of observing the α decay chains from isotopes of super heavy nuclei with Z = 122, 124, 126 and 128 and found that isotopes $^{298\text{-}307,311\text{-}314}$122, $^{305\text{-}308,315\text{-}322}$124, $^{318\text{-}320,323\text{-}327}$126 and $^{321\text{-}324,328\text{-}335}$128 can be synthesized and detected through alpha decay in laboratory [35]. In 2018, D. N. Poenaru et al. investigated various cluster radioactivity and alpha decay process for the synthesis of Z = 119 and 120 through the fusion of ^{248}Cm and ^{54}Cr [36]. The prediction of the existence of various isotopes with Z = 122, 124, 126 and 128 motivated us to perform the study present in this work.

THE COULOMB AND PROXIMITY POTENTIAL MODEL FOR DEFORMED NUCLEI (CPPMDN)

In the Coulomb and the Proximity Potential Model, the interaction potential barrier is taken as the sum of Coulomb, proximity and centrifugal potentials for the touching configuration and for the separated fragments. For the overlap region (pre-scission), a simple power law interpolation proposed by Y.J. Shi and W.J. Swiatecki [37] is used. The empirical form of the Coulomb and Proximity potential introduced by Shi and Swiatecki and its various versions were extensively used for decades by many researchers in the Preformed Cluster Model and for studying the fusion cross section [38, 39]. Importance of the proximity potential is that when it is introduced, the height of the potential barrier is reduced so that the theoretical predictions closely agree with the experimental findings. For a parent nucleus exhibiting exotic decay, the interacting potential barrier can be written as;

$$V = \frac{Z_1 Z_2 e^2}{r} + V_p(z) + \frac{\hbar^2 l(l+1)}{2\mu r^2} \quad ; \quad \text{for} \quad z > 0 \qquad (1)$$

In the above expression, Z_1 and Z_2 are the atomic numbers of the daughter and the emitted cluster, z is the distance between the near surface of the fragments, r is the distance between the fragment centers, which is given as $r = z + C_1 + C_2$. The quantity l is the angular momentum quantum number, μ is the reduced mass and $V_p(z)$ is the proximity potential. The proximity potential is given by Blocki et al [40, 41] as;

$$V_p(z) = 4\pi\gamma b \left[\frac{C_1 C_2}{(C_1 + C_2)}\right] \Phi\left(\frac{z}{b}\right) \qquad (2)$$

where, γ is the nuclear surface tension coefficient, b is the width of nuclear

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surface (diffuseness), C_i are Siissmann central radii and Φ , the universal proximity potential. These equations are applied to spherical nuclei.

The nuclear surface tension coefficient [41] is given by,

$$\gamma = 0.9517\left[1-1.7826\left(N-Z\right)^2/A^2\right] \text{ MeV / fm}^2 \quad (3)$$

where, N, Z and A represents the neutron number, proton number and mass number of the nucleus. The universal proximity potential [41] is given by the expression;

$$\Phi(\varepsilon) = -4.41e^{-\varepsilon/0.7176}, \text{for } \varepsilon \geq 1.9475 \quad (4)$$

and;

$$\Phi(\varepsilon) = -1.7817 + 0.9270\varepsilon + 0.0169\varepsilon^2 - 0.05148\varepsilon^3 \text{ for } 0 \leq \varepsilon \leq 1.9475 \quad (5)$$

where $\varepsilon = (z/b)$ with $b \approx 1$. The Siissmann central radii C_i of fragments are related to the sharp radii R_i as;

$$C_i = R_i - \left(\frac{b^2}{R_i}\right) \quad (6)$$

The sharp radii R_i can be calculated by using an empirical formula in terms of the mass numbers A_i as [40];

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3} \quad (7)$$

The potential for the overlap region of the barrier is given as;

$$V = a_0\left(L - L_0\right)^n, \text{ for } z < 0 \quad (8)$$

In this expression, $L = z + 2C_1 + 2C_2$ and $L_0 = 2C$. The constant a_0 and the parameter n are determined by the smooth matching of the two potentials at the touching point.

The barrier penetrability P can be obtained by using one dimensional WKB approximation and is given as;

$$P = \exp\left\{-\frac{2}{\hbar}\int_a^b \sqrt{2\mu\left(V-Q\right)}dz\right\} \quad (9)$$

where a and b are the turning points given by, $V(a) = V(b) = Q$ and Q is the energy released in the decay process.

Also $\mu = mA_1A_2/A$ is the reduced mass with A_1 and A_2 are the mass numbers of the emitted daughter and cluster nuclei respectively.

This integral can be evaluated numerically or analytically to get the half life time of decay as;

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{\nu P} \quad (10)$$

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where, $\nu = \frac{\omega}{2\pi} = \frac{2E_V}{h}$, the number of assaults on the barrier per second and E_V is the empirical zero-point vibration energy given by;

$$E_V = Q\left\{0.056 + 0.039\exp\left[\frac{(4-A_2)}{2.5}\right]\right\}, \text{ for } A_2 \geq 4 \tag{11}$$

The Coulomb and Proximity modal was modified by K P Santhosh et.al in 2002 [42] for deformed nuclei by considering the potential-energy barrier as the sum of the deformed Coulomb potential including higher multi-pole deformation [43, 44] , the deformed two term proximity potential [45], and the centrifugal potential for the touching configuration and for the separated fragments.

The Coulomb interaction between two deformed and oriented nuclei with higher order multipole deformation is given by,

$$V_C = \frac{Z_1 Z_2 e^2}{r} + 3Z_1 Z_2 e^2 \sum_{\lambda,i=1,2} \frac{1}{2\lambda+1}\frac{R_{0i}^{\lambda}}{r^{\lambda+1}} Y_{\lambda}^{(0)}(\alpha_i)\left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2 Y_{\lambda}^{(0)}(\alpha_i)\delta_{\lambda,2}\right] \tag{12}$$

$$\text{with } R_i(\alpha_i) = R_{0i}\left[1+\beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i)\right] \tag{13}$$

where R_{0_i} is given by equation (7) and α_i is the angle between the radius vector and the symmetry axis of the nuclei in the i^{th} site.

The two-term proximity potential for the interaction between a deformed and a spherical nucleus is given as [45];

$$V_{P2}(R,\theta) = \left\{2\pi\left(\frac{R_1(\alpha)R_C}{R_1(\alpha)+R_C+S}\right)^{1/2}\left(\frac{R_2(\alpha)R_C}{R_2(\alpha)+R_C+S}\right)^{1/2} \times\left[\varepsilon_0(S) + \frac{R_1(\alpha)+R_C}{2R_1(\alpha)R_C}\varepsilon_1(S)\right]^{1/2}\left[\varepsilon_0(S) + \frac{R_2(\alpha)+R_C}{2R_2(\alpha)R_C}\varepsilon_1(S)\right]^{1/2}\right\} \tag{14}$$

In this expression, θ represents the angle between the symmetry axis of the deformed nuclei and the line joining the centers of the two nuclei that are interacting and α is the angle

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between the radius vector and the symmetry axis of the nuclei. $R_1(\alpha)$, $R_2(\alpha)$ and R_C represents the are the principal radii of the curvature of the daughter nuclei and the radius of the spherical cluster respectively. The quantity, *S* is the distance between the surfaces along the straight line connecting the fragments. The functions $\varepsilon_0(S)$ and $\varepsilon_1(S)$ are the one-dimensional slab-on-slab functions.

FORMULAE FOR SPONTANEOUS FISSION AND ALPHA DECAY

Spontaneous fission (SF) half-life is an important factor in explain the stability of synthesized superheavy nuclei. Many empirical formulae were proposed for calculating the SF half-life.

***1. Empirical formula of K P Santhosh et al.*:** Considering the effects of the fissionability parameter $\frac{Z^2}{A}$ and the isospin effect $\left(\frac{N-Z}{N+Z}\right)$, in 2010, K P Santhosh et al., [46] proposed an empirical formula for the calculation of SF half-life and is given by,

$$\log_{10}(T_{1/2}/yr) = a\frac{Z^2}{A} + b\left(\frac{Z^2}{A}\right)^2 + c\left(\frac{N-Z}{N+Z}\right) + d\left(\frac{N-Z}{N+Z}\right)^2 + e \quad (16)$$

where the constants are a = −43.25203, b = 0.49192, c = 3674.3927, d = −9360.6 and e = 580.75058.

***2. Modified empirical formula of K P Santhosh et al.*:** In 2017, the same group has modified the formula by including a shell correction term [47]. The new formula is;

$$\log_{10}(T_{1/2}/yr) = a\frac{Z^2}{A} + b\left(\frac{Z^2}{A}\right)^2 + c\left(\frac{N-Z}{N+Z}\right) + d\left(\frac{N-Z}{N+Z}\right)^2 + eE_{shell} + f \quad (17)$$

Here the constants are a = −43.25203, b = 0.49192, c = 3674.3927, d = −9360.6, e = 0.8930 and f = 578.56058. E_{shell} is the shell correction energy taken from the mass tables of Möller et al., [48].

***3. Universal decay law for alpha and cluster decay* (UDL):** In 2009, Qi et al. [49], proposes a universal decay law which is applicable to both alpha and cluster decays and is give as;

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$$\log_{10} T_{1/2} = aZ_cZ_d\sqrt{\mu}Q_c^{-1/2} + b\sqrt{\mu Z_cZ_d\left(A_c^{1/3}+A_d^{1/3}\right)} + c \quad (18)$$

where $\mu = \frac{A_cA_d}{A_c+A_d}$, the reduced mass and the constants *a*, *b* and *c* corresponding to alpha and cluster decay are taken from the reference [49].

***4. Empirical formula of Horoi et al*.:** Horoi et al. [50] introduced an empirical formula to determine the half-lives of both the alpha and cluster decays and is given by;

$$\log_{10} T_{1/2} = \left(a_1\mu^x + b_1\right)\left[\left(Z_cZ_d\right)^y Q^{-1} - 7\right] + \left(a_2\mu^x + b_2\right) \quad (19)$$

The value of the parameters are;a_1 = 9.1, b_1 = −10.2, a_2 = 7.3, b_2 = −23.2, x = 0.416 and y = 0.613.

***5. Unified formula of Ni et al* (UD):** In 2008 Dongdong Ni et al. [51], proposed a unified formula to estimate the decay half-lives of alpha decay and cluster radioactivity. It is given as;

$$\log_{10} T_{1/2} = aZ_cZ_d\sqrt{\mu}Q_c^{-1/2} + b\sqrt{\mu Z_cZ_d} + c \quad (20)$$

where a = 0.39961, b = -1.31008, $c_{e\text{-}e}$ = -17.00698, $c_{e\text{-}o}$ = -16.26029, $c_{o\text{-}e}$ = -16.40484 and $c_{o\text{-}o}$ = -15.85337.

RESULTS AND DISCUSSION

First, we have calculated the spontaneous decay half-lives of $^{290\text{-}322}122$ parent nuclei using the formula of KPS (2010) and modified formula of KPS (2017). It is well known that the estimated value of spontaneous half-life depends strongly on the formula used. When comparing with the formula of KPS (2010), in KPS (2017), it can be seen that the SF half-life is reduced by an order of magnitude when the shell effects are included. However, in all the three cases we could see that the SF half-life is considerably larger $\left(1 < T_{1/2} < 10^{30}\ \text{sec}\right)$ for the parent isotopes in the rage A = 290-312. The plot of SF half-life verses the mass number of parents are given in **figure 1**. Maximum value of spontaneous decay half-life is obtained for $^{298}122$ in all the three plots.

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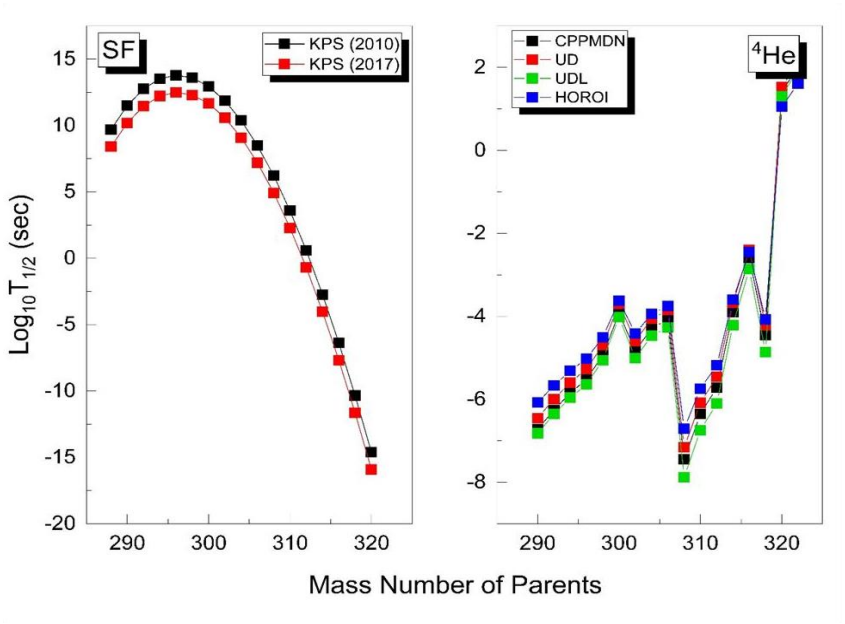


Fig. 1: Spontaneous fission and alpha decay half-lives of $^{290\text{-}322}$122 even-even parents

The alpha decay half-lives are calculated using the CPPMDN, UD, UDL and formula of Horoi et al., and the results are plotted in fig.1. The Q- values for the alpha and other cluster emissions are calculated using the expression;

$$Q = \Delta M(A,Z) - \sum_{i}^{n} \Delta M(A_i, Z_i) \qquad (20)$$

where $\Delta M(A,Z)$ and $\Delta M(A_i, Z_i)$ are the mass excess of the parent and the emitted nuclei respectively. For alpha and cluster emission, *n* varies from 1 to 2. The mass excess values are taken from the tables of Koura- Tachibana- Uno-Yamada KTUY [52]. From the figure it is clear that alpha decay half-life is most of the nuclei are greater than 10^{-6} seconds, which is the current experimental lower limit for the detection [53]. Therefore, for the parent nuclei $^{290\text{-}312}$112, the alpha decay dominates over SF and can be detected through the measurement of alpha decay half-lives. The calculated values of SF half-lives and alpha decay half-lives are given in table 1. In **table 1**, the results of our calculations of alpha decay half-lives are compared with the values obtained in ref. [54]. From the table it can be seen that the results given by CPPMDN, UD, UDL the formula of Horoi are in good agreement. Also, they are in agreement with the values given in ref [54]. Therefore, these models are equally good in predicting the alpha decay half-lives of superheavy elements.

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Table 1: The half-lives of spontaneous fission and alpha decay of $^{290\text{-}322}122$ even-even nuclei

Parent Nuclei	Q_α(MeV)	$\log_{10} T_{1/2}$(sec)							
		Spontaneous Fission			Alpha Decay				
		Xu (2008)	KPS (2010)	KPS (2017)	CPPMDN	UD	UDL	HOROI	Ref. [62]
$^{290}122$	14.025	25.832	11.493	10.196	-6.725	-6.453	-6.820	-6.078	---
$^{292}122$	13.775	28.217	12.758	11.461	-6.256	-5.993	-6.357	-5.667	---
$^{294}122$	13.565	29.887	13.517	12.220	-5.853	-5.597	-5.962	-5.312	-7.377
$^{296}122$	13.395	30.843	13.788	12.491	-5.519	-5.269	-5.641	-5.019	-7.167
$^{298}122$	13.105	31.084	13.592	12.295	-4.935	-4.696	-5.055	-4.507	-7.966
$^{300}122$	12.625	30.611	12.946	11.649	-3.925	-3.704	-4.017	-3.621	-6.217
$^{302}122$	13.055	29.424	11.870	10.573	-4.833	-4.594	-5.010	-4.415	-6.037
$^{304}122$	12.795	27.523	10.378	9.081	-4.289	-4.061	-4.466	-3.938	-7.881
$^{306}122$	12.695	24.909	8.490	7.193	-4.076	-3.851	-4.272	-3.750	-8.114
$^{308}122$	14.425	21.581	6.219	4.922	-7.749	-7.160	-7.876	-6.704	-9.099
$^{310}122$	13.825	17.541	3.582	2.285	-6.651	-6.082	-6.744	-5.741	-8.529
$^{312}122$	13.495	12.788	0.592	-0.705	-5.916	-5.459	-6.103	-5.184	-6.332
$^{314}122$	12.615	7.3220	-2.735	-4.032	-4.103	-3.679	-4.213	-3.595	-4.232
$^{316}122$	12.035	1.1440	-6.387	-7.684	-2.901	-2.401	-2.865	-2.453	-2.502
$^{318}122$	12.875	-5.7406	-10.350	-11.647	-4.958	-4.223	-4.863	-4.079	13.10
$^{320}122$	10.485	-13.348	-14.613	-15.910	1.394	1.522	1.308	1.052	2.268
$^{322}122$	10.265	-21.662	-18.562	-20.459	1.834	2.150	1.955	1.613	-6.361

It is to be noted that UD and the formula Horoi et al., are like a preformation model because, the alpha particle and cluster preformation probabilities are included in it. Since the preformation probability of light clusters inside the parent nucleus is larger, the emission of light clusters can be predicted by this formula with high accuracy. The formula of Qi et al., can be considered like a preformation model as well as a fission-like model. Therefore, it can be used for studying the emission of both light and heavy clusters. The CPPM and CPPMDN were successfully used by K P Santhosh et al., [55,56.57,58] for studying various aspects of cluster decay and the results are found in agreement with the predictions made by other models such as Viola-Seaborg-Sobiczewski semi-empirical (VSS) relation[59], the universal (UNIV) curve of Poenaru et al. [60], universal decay law (UDL), analytical formula of Royer [61] etc.

The main objective of our study is to investigate the competition between the most probable light cluster emission and halo emission from the selected parent nuclei. We have considered the emission of $^{6\text{-}10}$Li, $^{8\text{-}12}$Be, $^{10\text{-}14}$B, $^{12\text{-}17}$C, $^{14\text{-}18}$N, $^{16\text{-}24}$O, $^{18\text{-}27}$F and $^{20\text{-}29}$Ne by calculating the half-life of decay using the CPPMDN. In 2008, K P Santhosh et al., studied the cluster and alpha emission of Z = 122 nuclei within the framework of the Coulomb and Proximity Potential Model (CPPM) [54],

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by computing the Q- values using the experimental binding energies of Audi and Wapstra [62] and using the tables of Möller at al. [48]. In this article we have calculated the decay half-life of cluster and halo nuclei by including the effect of quadrupole (β_2) and hexadecapole (β_4) deformations using the CPPMDN. For the calculation with CPPMDN, the values of the deformation parameters β_2 and β_4 are taken from reference [48].The decay half-lives were also calculated using UD, UDL and the formula of Horoi et al. From our calculations, it is clear that emission of clusters ^{8}Be, ^{11}B, ^{12,13,14}C, ^{15}N, ^{16,18}O, ^{23}F and ^{22,24}Ne is possible from many of the parent nuclei with a half-life less than the experimental upper limit of 10^{30} seconds. However, the most probable clusters in each isotope family are ^{8}Be, ^{11}B, ^{12,14}C, ^{15}N, ^{18}O, ^{23}F and ^{24}Ne. The decay half-lives of these clusters calculated within CPPMDN, UD, UDL and formula of Qi et al., are given in **table 2.**

Table 2: The half-lives of the most probable light cluster and halo emission from $^{290\text{-}322}$122 even-even parent nuclei

Parent Nuclei	Emitted Cluster	Emitted Halo	Q-Value (MeV)	$\log_{10} T_{1/2}$(sec)			
				CPPMDN	UD	UDL	HOROI
^{290}122	^{8}Be		24.81	14.13	9.25	15.79	13.64
	^{11}B		29.82	26.46	19.18	29.40	26.08
	^{12}C		46.90	13.59	3.51	14.35	13.22
	^{14}C		43.15	20.44	11.38	23.52	21.87
	^{15}N		52.83	22.42	9.72	23.45	21.78
	^{18}O		64.90	20.45	6.31	21.91	20.45
	^{24}Ne		84.25	25.31	6.06	25.93	27.61
^{292}122	^{8}Be		24.22	15.31	10.51	17.12	14.83
	^{11}B		29.74	26.55	19.37	29.53	26.26
	^{12}C		46.90	13.13	3.51	14.25	13.22
	^{14}C		42.62	21.32	12.34	24.46	22.74
	^{15}N		52.00	23.61	11.05	24.78	22.93
	^{18}O		64.22	21.59	7.30	22.85	22.75
	^{24}Ne		83.83	25.77	6.64	26.34	28.13
^{294}122	^{8}Be		23.74	16.30	11.58	18.22	15.82
	^{11}B		29.15	27.98	20.77	30.97	27.56
	^{12}C		46.12	14.66	4.67	15.42	14.24
	^{14}C		42.12	22.17	12.27	23.36	23.58
	^{15}N		50.95	25.14	12.78	26.53	24.42
	^{18}O		63.33	22.47	8.61	24.14	23.86
	^{24}Ne		83.23	26.55	7.47	26.98	28.81
^{296}122	^{8}Be		23.45	16.92	12.25	18.87	16.45
	^{11}B		28.94	28.42	21.29	31.44	28.04
	^{12}C		45.23	16.07	6.04	16.79	15.44
	^{14}C		41.79	22.73	13.89	25.93	24.14
	^{15}N		50.11	26.39	14.21	27.96	25.65
	^{18}O		62.47	23.56	9.91	25.41	24.96
	^{24}Ne		82.67	27.28	8.26	27.57	29.47
^{298}122	^{8}Be		22.94	18.02	13.45	20.11	17.56
	^{11}B		28.57	29.33	22.21	31.33	32.35
	^{12}C		44.51	17.22	7.18	17.93	16.44
	^{14}C		41.56	23.13	14.34	26.30	24.54
	^{15}N		49.31	27.62	15.60	29.35	26.85
	^{18}O		61.62	24.84	11.22	26.70	26.06
	^{24}Ne		82.12	28.01	9.04	28.17	30.08

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$^{300}122$	^{8}Be		22.19	18.02	15.30	22.04	19.27
	^{12}C		43.74	18.49	8.42	19.18	17.52
	^{14}C		40.95	24.21	15.51	27.47	25.60
	^{15}N		48.39	29.06	17.24	29.35	28.27
	^{18}O		60.37	27.04	13.19	28.70	27.73
	^{24}Ne		81.11	29.52	10.49	29.37	31.25
$^{302}122$	^{8}Be		22.02	20.12	15.74	22.44	19.67
	^{12}C		42.81	24.29	9.96	27.49	25.60
	^{14}C		40.90	20.09	15.61	20.76	18.88
	^{15}N		48.01	29.66	17.94	31.66	28.87
	^{18}O		59.98	27.51	13.82	29.26	28.27
$^{304}122$	^{8}Be		22.02	20.11	15.74	22.39	19.67
	^{12}C		42.34	20.87	10.77	21.54	19.59
	^{14}C		40.97	24.16	15.48	27.25	25.58
	^{15}N		47.83	29.95	18.27	31.91	29.17
	^{18}O		59.79	28.02	14.14	29.47	28.54
$^{306}122$	^{8}Be		21.83	20.56	16.23	22.85	20.13
	^{12}C		42.12	21.19	11.15	21.85	19.93
	^{14}C		41.27	23.62	14.91	26.53	25.07
	^{15}N		48.54	28.79	16.99	30.42	28.07
	^{18}O		59.85	27.46	14.05	29.25	28.47
$^{308}122$	^{8}Be		23.28	17.26	12.66	18.94	16.84
	^{11}B		28.06	28.93	19.41	28.92	26.32
	^{12}C		42.10	21.14	11.19	21.81	19.96
	^{14}C		43.41	19.91	10.96	22.18	21.52
	^{15}N		49.84	26.74	14.71	27.85	26.11
	^{18}O		61.82	23.77	10.93	25.77	25.86
	^{24}Ne		80.92	29.11	10.79	29.16	31.53
$^{310}122$	^{8}Be		24.39	14.93	10.16	16.17	14.52
	^{11}B		31.07	22.29	16.39	25.58	23.54
	^{12}C		43.47	18.49	8.88	19.23	17.94
	^{14}C		45.00	17.02	8.22	19.12	19.06
		^{15}C	39.46	27.04	19.69	31.77	30.25
	^{15}N		51.04	24.91	12.68	25.55	24.37
	^{18}O		63.75	20.33	8.03	22.52	23.42
	^{24}Ne		82.70	25.91	8.27	26.72	29.52
$^{312}122$	^{8}Be		23.61	16.54	11.91	18.00	16.14
	^{11}B		32.11	19.73	14.16	23.10	21.50
	^{12}C		44.46	16.62	7.28	17.41	16.55
	^{14}C		46.23	14.68	6.19	16.83	17.24
		^{15}C	41.04	23.31	16.44	28.16	27.30
	^{15}N		51.95	23.55	11.19	23.83	23.08
	^{18}O		64.74	18.49	6.60	20.84	22.22
	^{23}F		70.15	29.99	14.12	31.02	32.74
	^{24}Ne		84.19	23.25	6.22	24.71	27.88
$^{314}122$	^{8}Be		22.41	19.20	14.77	21.03	18.79
	^{11}B		30.63	23.21	17.37	26.49	24.46
	^{12}C		45.20	15.23	6.12	16.06	15.53
	^{14}C		46.53	13.86	5.71	16.22	16.81
		^{15}C	41.54	22.11	15.46	27.00	26.41
	^{15}N		52.01	23.46	11.09	23.63	23.01
	^{18}O		64.91	17.98	6.35	20.46	22.02
	^{23}F		71.31	27.88	12.29	28.91	31.24
		^{24}F	67.94	28.96	18.42	35.65	36.96
	^{24}Ne		84.86	21.98	5.32	23.76	27.17
$^{316}122$	^{8}Be		21.18	22.15	17.95	24.41	18.79
	^{11}B		29.23	26.72	20.63	29.93	27.47
	^{12}C		43.56	18.16	8.74	18.81	17.83
	^{14}C		44.93	16.68	8.34	18.97	19.18
		^{15}C	40.79	23.68	16.95	28.52	27.78

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	^{15}N		49.95	26.57	14.54	27.24	25.98
	^{18}O		64.80	18.15	6.51	20.51	22.16
	^{23}F		71.70	27.09	11.69	28.12	30.75
		^{24}F	68.76	27.20	17.04	34.02	35.82
	^{24}Ne		20.34	24.32	5.18	26.88	23.91
^{318}122	^{8}Be		84.82	21.71	20.30	23.58	27.24
	^{12}C		42.63	21.59	12.03	22.27	20.71
	^{14}C		43.24	20.02	11.28	22.05	21.83
		^{15}C	39.43	26.72	19.77	31.47	30.35
	^{18}O		62.37	22.18	10.12	24.28	25.20
	^{23}F		71.87	26.68	11.44	27.71	30.55
		^{24}F	69.15	28.20	16.40	33.18	35.30
	^{24}Ne		84.82	21.70	5.38	23.58	27.24
^{320}122	^{12}C		39.77	25.22	28.57	25.84	23.68
	^{14}C		39.42	27.06	18.61	29.87	28.44
	^{24}Ne		82.17	26.01	9.05	26.83	30.19

The plots of logarithmic value of decay half-lives verses the neutron number of parents are given in **figures 2-5**. From **fig. 2**, we can see that the emission of ^{8}Be is possible from $^{290\text{-}318}$122 even-even nuclei and the emission of ^{11}Be is possible from ^{290,292}122 and $^{308\text{-}316}$122 even-even nuclei with $T_{1/2} < 10^{30}$ sec. **Fig. 3** shows that the emission of ^{12}C is possible from $^{290\text{-}320}$122 parent nuclei. Also, the emission of ^{14}C is possible from the selected parent nuclei. The possibility for the emission of ^{15}N from $^{290\text{-}318}$122 even-even nuclei and ^{18}O from parent nuclei $^{290\text{-}298,\ 308\text{-}320}$ 122 even-even nuclei is evident from **fig. 4**. From **fig. 5** we can see that the emission of ^{23}F is possible only from $^{314\text{-}318}$122 parent nuclei with a decay half-life less than the experimental upper limit. The emission of ^{24}Ne from $^{290\text{-}294,\ 310\text{-}320}$122 even-even parents is also evident from **fig. 5**. Further, in all these plots, there is a kink at parent neutron number N_P = 184, which indicates the stability of the parent nuclei due to neutron shell closure and is stable against the cluster decay. It is to be noted that 184 is already predicted as a neutron magic number by many theoretical models [20-23] and shell effects has an important role in determining the cluster decays. Also, in these plots there is a dip around N_P = 190 correspond to the maximum possibility for the formation of a daughter nucleus with closed neutron shells.

For the comparison between the decay probability of cluster and halo nuclei from the selected parent nuclei, we have considered the emission of neutron halo nuclei ^{6,8}He, ^{11}Li, ^{11,12,14}Be, ^{14}B, ^{15,17}C, ^{22}N, ^{23}O, ^{24,26}F and ^{29}Ne from the selected parent nuclei. The identification of neutron halo structure is possible through the calculation neutron separation energy and driving potentials.

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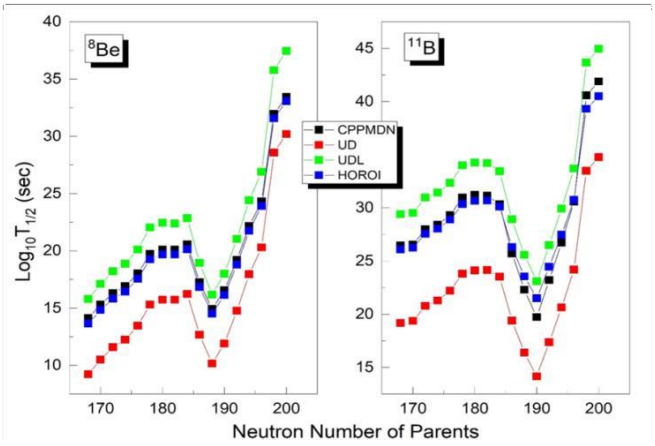


Fig. 2: Plot of $\log_{10} T_{1/2}$ ***verses the neutron number of parents for the emission of*** ^{8}***Be and*** ^{11}***B clusters from*** $^{290\text{-}322}$***122 even-even parent nuclei***

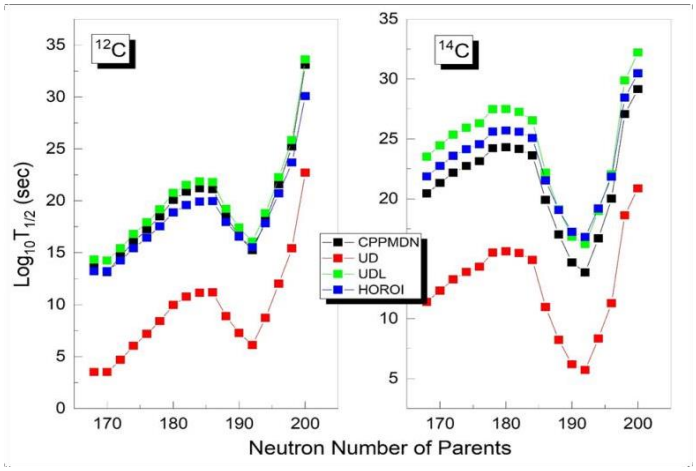


Fig. 3: Plot of $\log_{10} T_{1/2}$ ***verses the neutron number of parents for the emission of*** ^{12}***C and*** ^{14}***C clusters from*** $^{290\text{-}322}$***122 even-even parent nuclei***

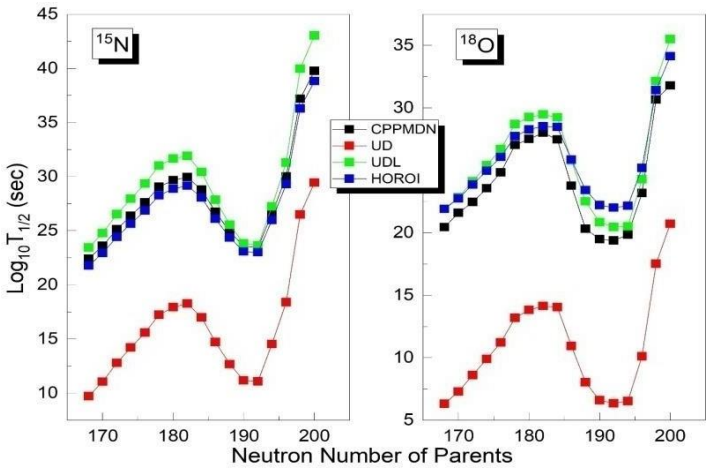


Fig. 4: Plot of $\log_{10} T_{1/2}$ ***verses the neutron number of parents for the emission of*** ^{15}***N and*** ^{18}***O clusters from*** $^{290\text{-}322}$***122 even-even parent nuclei***

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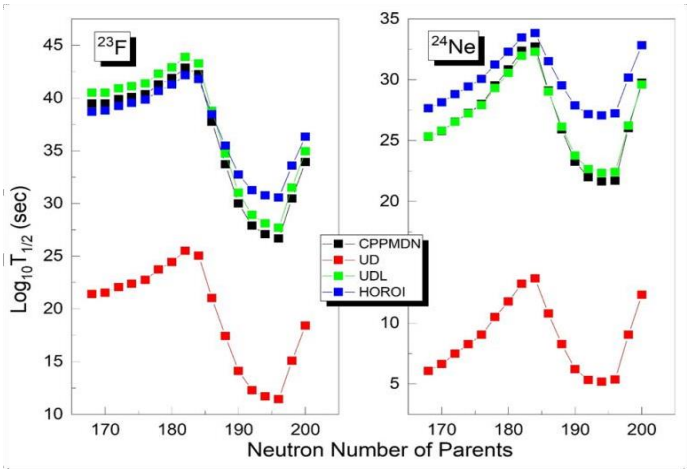


Fig. 5: Plot of $\log_{10} T_{1/2}$ ***verses the neutron number of parents for the emission of*** ^{15}***C and*** ^{24}***F halo nuclei from*** $^{290\text{-}322}$***122 even-even parent nuclei***

The details of such calculations are given in reference [13], and for our calculation, the halo candidates are taken from this work. The decay characteristics of these halo nuclei from $^{290\text{-}322}$122 even-even nuclei were determined using the CPPMDN, UD, UDL and the formula of Horoi et al. Since the halo is a highly deformed structure, it is characterized by a large rms radius. The expression for radius $R_i = R_0 A_i^{1/3}$ cannot represent the structure of the halo nuclei completely. To some extend the surface effects are included in the Siismann central radii (C_i); however, R_i is a function of A_i alone. For a deformed halo structure, the rms radius is found to be larger than its normal radius. For our calculation using CPPMDN, the rms radius for halo nuclei is taken from the work of S Ahmed et al. [63]. Even though we have considered the emission possibility of 14 neutron halo nuclei from $^{290\text{-}322}$122, from our calculations we could see that only ^{15}Cand ^{24}F shows possibility for the emission from the selected parent nuclei with a decay half-life less than the experimental upper limit of 10^{30} seconds and such results are also included in **table 2**. From the table it can be seen that the parent nuclei with A < 310 are not emitting halo nuclei but parents with $310 \le A \le 318$ are halo emitters. From our calculations, it is clear that the inclusion of rms radius in the calculation considerably lowered the value of decay half-life when compared with the results obtained from UDL and formula of Horoi for the emission from many parent nuclei. Such lowering was not observed in the case of normal clusters; UDL and formula of Horoi gave values which are closer to that obtained using CPPMDN.

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The plot of logarithmic value of decay half-life verses the neutron number of parents for the emission of ^{15}C and ^{24}F from $^{290\text{-}322}$122 is given in **figure 6**. From the figure it is clear that the emission of halo nucleus ^{15}C is possible from $^{310\text{-}318}$122 parent nuclei with a half-life within the experimental limit. In the case of ^{24}F halo, CPPMDN predicts the possibility of emission from ^{314,316,318}122. The UDL and the formula of Horoi et al. predicts decay half-lives greater than the experimental upper limit. In these plots also there is a kink at N_P = 184, which indicates the stability of parent nuclei against the decay of halo nuclei. Also, the dip at N_P = 192 in the plot of ^{15}C and at N_P = 196 in the plot of ^{24}F indicates the formation possibility of daughter nuclei with closed neutron shell structure.

On comparing the results obtained using CPPMDN, UD, UDL and the formula of Horoi et al, we could see that CPPMDN, UDL and the formula of Horoi are equally good in predicting the decay characteristics of the emission of light cluster from superheavy elements. The results obtained using CPPMDN, UDL and Horoi formula are in close agreement with a maximum deviation of 5.54 in the value of $\log_{10} T_{1/2}$ in the case of ^{24}Ne. The results obtained through UD is agreement with the results of other formulae only in the case of very light clusters like alpha. When the mass of the cluster increases, the UD formula gives much lower values for decay half-lives than given by the other models which is evident from the plots and from the **table 2**.

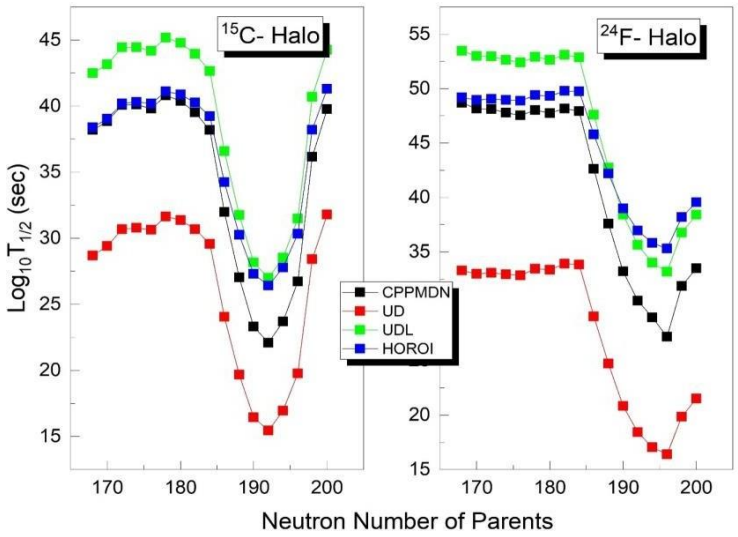


Fig 6: Plot of $\log_{10} T_{1/2}$ ***verses the neutron number of parents for the emission of ^{15}C and ^{24}F halo nuclei from $^{290\text{-}322}$122 even-even parent nuclei***

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To find the relative accuracy of CPPMDN, UDL, HOROI, and UD models used in the present work, we have made a calculation of alpha decay half-lives of some superheavy nuclei with Z = 110 – 118 using these models and compared with their experimental values given in ref [64]. Using the calculated and experimental alpha decay half-lives, the statistical parameter, the rms deviation was computed using the expression,

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\Delta_i^2\right)} \qquad (21)$$

where, $\Delta_i = \log_{10} T_{\exp} - \log_{10} T_{cal}$, is the deviation of the calculated logarithm of half-life from the experimental one and *N* is the number of superheavy nuclei under study. The results of these calculations are given in the second column in table 3. A minimum value of rms deviation indicates the more accurate prediction. From the values of rms deviations, we can see that the CPPMDN is good predicting the experimental half-life values compared to UDL, HOROI and UD models.

Further, to analyze the consistency of the models used in the present work and to see that how close the predictions made by the models are, we have computed the rms deviation of each model with respect to the other. That is, to measure the consistency of CPPMN with UDL, we can define $\Delta = \log_{10} T_{UDL} - \log_{10} T_{CPPMDN}$ and similarly between other models. Then the rms deviation of CPPMDN with respect to UDL is calculated using the equation (21). Similarly, the rms deviations CPPMDN with respect to HOROI model, CPPMDN with respect to HD etc., are computed using the same procedure. The results of the calculations are given in the fourth column in **table 3**.

Table 3: Statistical comparison between CPPMDN, UDL, HOROI and UD formulae. Column 2: rms deviations calculated w.r.t experimental values of alpha emission half-lives of some Z = 110 – 118 taken from ref. [64]. Column 4: rms deviations of one model w.r.t other.

Model	rms deviations	Model	rms deviations
CPPMDN	0.4982	CPPMDN/UDL	0.3035
UDL	0.6420	CPPMDN/HOROI	0.5089
HOROI	0.5276	CPPMDN/UD	0.2354
UD	0.6346	UDL/HOROI	0.7198
		UDL/UD	0.4926
		HOROI/UD	0.3088

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From the table, it can be seen that the predictions of alpha decay half-lives made by CPPMDN and UD are very close, with rms deviation 0.2354. Maximum deviations are exhibited by the predictions made by UDL and HOROI models with rms deviation 0.7198. However, it is to be noted that while predicting the half-life of the cluster and halo emissions, there is significant lowering in the half-lives predicted by UD formula compared to the predictions made by other models.

Finally, for better understanding of the competition between the decay of alpha particles and other clusters, a quantity called branching ratio (b) is usually defined. The branching ratio of cluster radioactivity with respect to corresponding alpha decays is defined as;

$$\log_{10} b_c = \log_{10}\left(\frac{\lambda_c}{\lambda_\alpha}\right) = \log_{10}\left(\frac{T_\alpha}{T_c}\right) \quad (22)$$

where λ_c and λ_α denotes the decay constants for cluster and alpha decay respectively. From this expression, it is clear that a positive value of $\log_{10} b_c$ denotes the domination of cluster radioactivity over the alpha decay. The logarithmic value of branching ratio of all the prominent clusters and halo with respect to the alpha decay is calculated and the results are plotted in **fig. 7**. Branching ratio for SF relative to alpha decay $(\log_{10} b_{SF})$ is also included in the same plot. The branching ratio for SF relative to alpha decay is defined as;

$$\log_{10} b_{SF} = \log_{10}\left(\frac{\lambda_{SF}}{\lambda_\alpha}\right) = \log_{10}\left(\frac{T}{\frac{\alpha}{T_{SF}}}\right) \quad (22)$$

where λ_{SF} and T_{SF} are the decay constant and decay half-life for spontaneous fission.

From **fig. 7** it is clear that the value of $\log_{10} b_c$ is negative for all the most probable clusters and halos. The value of $\log_{10} b_{SF}$ is also negative for the parents $^{290\text{-}312}112$. This means, alpha decay half-lives are much shorter than the cluster decay half-lives and SF half-lives for these parent nuclei and the preferred mode of decay of $^{290\text{-}312}112$ nuclei is alpha emission. For parent nuclei $^{314\text{-}322}122$ $\log_{10} b_{SF}$ is positive and hence decay through spontaneous fission. Even though the calculations based on CPPMDN, UD, UDL and formula of Horoi suggests that the alpha decay is the most favored mode of decay for many of the parent nuclei considered here, it can be seen that there is considerable probability for the emission of ^{8}Be, ^{11}B, ^{12,14}C, ^{15}N, ^{18}O,^{23}F and ^{24}Ne clusters and ^{15}C and ^{24}F halo nuclei with decay half-lives less than 10^{30} seconds and can be detected experimentally when emitted.

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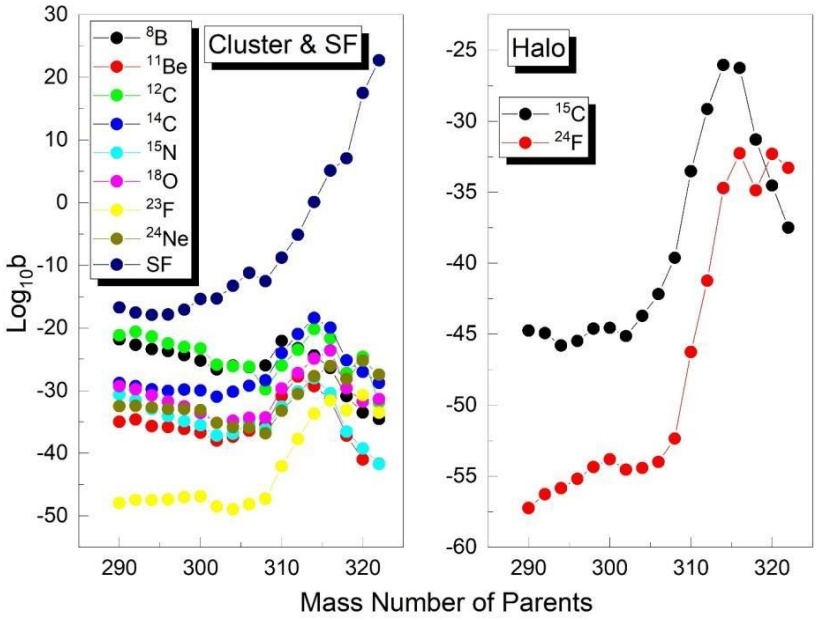


Fig 7: Plot of $\log_{10} b$ ***verses the mass number of parents for spontaneous fission, cluster emission and halo emission. The decay half-lives of alpha, cluster and halo emission from CPPMDN and SF half-life from KPS (2017)***

On comparing the emission probability of clusters and neutron halo nuclei, we can see that the emission probability of neutron halo is less than that for the cluster emission. For the parents $^{316\text{-}322}122$, the SF half-life is less than 1 micro seconds and cannot be detected with existing experimental facilities. Recently many researches are going on for the synthesis of superheavy elements beyond Z = 118. In this scenario we hope that our study on the emission probabilities of alpha, cluster and halo nuclei from $^{290\text{-}322}122$ nuclei will add to the existing knowledge and will be useful in exploring further details about the synthesis and decay characteristics of superheavy elements.

SUMMARY AND CONCLUSION

- A comparative study of the emission probability of light cluster, neutron halo $(Z \leq 10)$ and alpha particle and, spontaneous fission from $^{290\text{-}322}122$ even-even nuclei is made using the CPPMDN, UD, UDL and the formula of Horoi et al.
- Our calculations showed that ^{8}Be, ^{11}B, ^{12,14}C, ^{15}N, ^{18}O, ^{23}F and ^{24}Ne are the most probable clusters of each isotope family with $Z \leq 10$ to decay from the selected parent nuclei.
- Even though we have analyzed the decay properties of ^{6,8}He, ^{11}Li, ^{11,12,14}Be, ^{14}B, ^{15,17}C, ^{22}N, ^{23}O, ^{24,26}F and ^{29}Ne neutron halo nuclei, only ^{15}C

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and ^{24}F showed the possibility for decay from the parents with a half-life within the experimental upper limit.

- The parents $^{290\text{-}308,320}$122 are cluster emitters and $^{310\text{-}318}$122 are both cluster and halo emitters with a decay half-life less than the experimental limit of 10^{30} seconds and can be detected when emitted.
- For the calculation of decay half-life of halo nuclei using CPPMDN, we have used the rms radius of the halo nuclei in place of their normal radius.
- The kink at N_P = 184 in the plot of $\log_{10} T_{1/2}$ verses the neutron number of parents shows the neutron shell closure at this neutron number that provides exemptional stability to the nucleus.
- The fission like models, CPPMDN, UDL and the formula of Horoi can be used to predict the decay properties of light clusters and halo nuclei from superheavy elements. But the Unified formula (UD), which is like a preformation model, can be used to predict the decay properties of alpha decay from superheavy nuclei, but for cluster and halo emissions, it predicts much lower values than predicted by other models
- The SF half-life is calculated using the formula of KPS (2010) and modified formula of KPS (2017). Calculations showed that for the parent nuclei $^{290\text{-}312}$112, the alpha decay dominates over SF and can be detected through the measurement of alpha decay half-lives. For the parents $^{314\text{-}322}$122, the SF half-lives are much less than 10^{-6} seconds and cannot be detected using current experimental facilities.
- The calculation of rms deviations of the models shows that CPPMDN is most accurate in predicting the decay-half lives than other models considered in this study.
- The calculation of branching ratio of cluster and halo emission relative to the alpha decay showed that alpha decay dominates over the cluster and halo emissions. The branching ratio of SF relative to alpha decay shows that for the parent nuclei $^{290\text{-}312}$112 the alpha decay is dominant and for the parents $^{314\text{-}322}$122, SF is dominant.
- With new developments in the reaction and detection facilities, we hope that new elements with Z > 118 will be synthesized in near future and our study will be useful for further experimental investigations.

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