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Cluster radioactivity in superheavy nuclei $^{299-302}120$

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The cluster radioactivity is an unusual decay process observed in superheavy nuclei. When a cluster nuclei are emitted, the residual or daughter nuclei is having doubly magic nuclei or it may be neighbourhood of the same. We have studied cluster radioactivity [^{4}He, ^{6}Li, ^{9}Be, ^{20,22}Ne, ^{23}N, $^{24-26}$Mg, $^{28-30}$Si, ^{31}P, $^{32-34}$S, ^{35}Cl, ^{36,38,40}Ar, $^{40-46}$Ca] in the superheavy nuclei $^{299-302}$120 using the nuclear and proximity model. The calculated cluster decay half-lives are compared with that of the other theoretical models such as Univ[1], NRDX[2], UDL[3] and Horoi[4]. From the comparison of different models we have observed that the cluster nuclei with ^{4}He, ^{9}Be, ^{22}Ne, ^{26}Mg, ^{30}Si, ^{34}S, ^{40}Ca and ^{46}Ca are having smaller logarithmic half-lives than the exotic cluster decay modes.

Keywords: Superheavy nuclei, Cluster radioactivity, Exotic cluster decay, Proximity model

1 Introduction

The cluster radioactivity is the process in which heavy nuclei disintegrates into asymmetric combination of fission fragments. It is the process in which it emits light nuclei from the parent nuclei. The cluster radioactivity has been the curiosity of the present consequences. The cluster radioactivity was observed during the year 1984[5-7]. Only few papers are available on both theoretical and experimental aspects of cluster radioactivity. Experiment[8-14] becomes crucial in discriminating different theoretical models of cluster radioactivity. The cluster decay is the intermediate of alpha and spontaneous fission. Recent discovery of superheavy elements play a very important role in the material world. The different decay modes of superheavy elements are found in experimental and theoretical works on cluster radioactivity. Ni and Ren[2] studied alpha decay rates and Xu and Ren[3] studied alpha decay using Density-dependent cluster model. Using quantum scattering process Sahu *et al*.[15] developed general decay formula for cluster radioactivity. Cui *et al*.[16] employed alpha decay half-lives from the study of different models in the heavy and superheavy region Z=80-118. Santhosh and Priyanka[17] studied competition between spontaneous fission and alpha decay in the superheavy region Z=99-129. Using generalized density-dependent cluster model, Qian and Ren[18] studied half-lives in the superheavy region. Zhang and Wang[19] used unified description formula to study cluster radioactivity in superheavy region Z≥118. Previous workers[20-24] studied exotic cluster decay in heavy and superheavy nuclei.

Using cluster preformation law, Wei and Zhang[25] investigated cluster radioactivity in the heavy and superheavy region. Poenaru *et al*.[26] studied branching ratios with respect to alpha decay half-lives in the superheavy region. Dong *et al*.[27] were studied alpha decay half-lives of superheavy nuclei using two potential approach. Previous workers[28-30] studied the decay properties and half-lives of the different decay modes in the superheavy region Z=121 and 125. Using liquid drop model Wang *et al*.[31] studied alpha decay and proton decay half-lives in neutron deficient nuclei. Earlier workers[32-40] studied different decay modes and the projectile-target combinations to synthesis the superheavy element. Hence, the purpose of our work is to identify cluster radioactivity [^{4}He, ^{6}Li, ^{9}Be, ^{20,22}Ne, ^{23}N, $^{24-26}$Mg, $^{28-30}$Si, ^{31}P, $^{32-34}$S, ^{35}Cl, ^{36,38,40}Ar, $^{40-46}$Ca] in the superheavy nuclei $^{299-302}$120. At the end we have compared our work with the Univ, NRDX, UDL and Horoi.

2 Theoretical Framework

The cluster radioactivity is the fission like process in which parent nuclei split into a daughter nuclei and

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a fragment nucleus. For a spherical daughter nuclei and fragment nuclei, the total potential is written as:

$$V(r) = V_n(r) + \frac{Z_1 Z_2 e^2}{r} + \frac{\ell(\ell+1)\hbar^2}{2\mu r^2} \quad \ldots (1)$$

The nuclear interaction between the two spherical nuclei is given by:

$$V_n(r) = 4\pi\gamma b \frac{C_1 C_2}{C_1 + C_2} \phi(\varepsilon) \quad \ldots (2)$$

here b is the nuclear surface width ≈ 1fm, C_i is the central radii of a nuclei, $\phi(\varepsilon)$ is the universal function[40] Which depends on $\varepsilon = (r - C_1 - C_2)/b$ and γ is the nuclear surface tension and given by

$$\gamma = \gamma_0 \left[1 - k(N-Z)^2 / A^2\right] MeV/fm^2 \quad \ldots (3)$$

where N is the neutron number, Z is the charge number and A is the mass number of parent nuclei. The γ_0 = 0.9517 and k = 1.7826[41]. The central radii in terms of sharp radius is given as:

$$C_i = R_i - \frac{b^2}{R_i} fm \quad \ldots (4)$$

and the sharp radii is expressed as

$$R_i = 1.28 A_i^{1/3} - 0.76 + 0.8 A_i^{-1/3} \quad \ldots (5)$$

For cluster radioactivity, the barrier penetrability P is evaluated numerically and analytically and it is expressed as:

$$P = \exp\left\{ -\frac{2}{\hbar} \int_a^b \sqrt{2\mu(V-Q)}\, dz \right\} \quad \ldots (6)$$

where reduced mass $\mu = \frac{A_1 A_2}{A_1 + A_2}$, where A_1, and A_2 are masses of daughter and emitted cluster, respectively. The turning points a and b are studied using the following condition $V(a) = Q$ and $V(b) = 0$. The half-life of cluster radioactivity is given by:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{\upsilon P} \quad \ldots (7)$$

where $\upsilon = \frac{\omega}{2\pi} = \frac{2E_\upsilon}{h}$, υ is the assault frequency and λ is the decay constant. The empirical vibration energy is expressed as:

$$E_\upsilon = Q\left\{0.056 + 0.039 exp\left[\frac{4 - A_2}{2.5}\right]\right\} \text{ for } A_2 \geq 4 \quad \ldots (8)$$

3 Results and Discussion

The amount of energy released during the cluster radioactivity is studied using the following equation;

$$Q = \Delta M(A, Z) - \Delta M(A_d, Z_d) - \Delta M(A_c, Z_c) \quad \ldots (9)$$

where $\Delta M(A, Z)$ is the mass excess of the parent, $\Delta M(A_d, Z_d)$ is the mass excess of daughter nuclei and $\Delta M(A_c, Z_c)$ is the mass excess of cluster nuclei. In the work, we have used both experimental and theoretical mass excess values available in the literature[42-46]. The amount of energy released during the emission of clusters such as ^{4}He, ^{6}Li, ^{9}Be, ^{20,22}Ne, ^{23}N, $^{24-26}$Mg, $^{28-30}$Si, ^{31}P, $^{32-34}$S, ^{35}Cl, ^{36,38,40}Ar, and $^{40-46}$Ca are plotted as function of mass number of clusters and depicted in Fig. 1. The variation of amount of energy released during cluster radioactivity with the neutron number of cluster is as shown in Fig. 2. From the Figs 1 and 2 it is observed that as the mass number of cluster/neutron number of cluster increases the amount of energy released also increases. It is observed from the two figures that the amount of energy released is higher for ^{40}Ca [Z=20, N=20], which may be due to the presence of magic nuclei. We have studied half-lives for different cluster emission such as ^{4}He, ^{6}Li, ^{9}Be, ^{20,22}Ne, ^{23}N, $^{24-26}$Mg, $^{28-30}$Si, ^{31}P, $^{32-34}$S, ^{35}Cl, ^{36,38,40}Ar, and $^{40-46}$Ca in the isotopes of $^{299-302}$120 as explained in detail in the theoretical frame work. The studied half-lives of different cluster emission with the neutron mass number is presented in Fig. 3. In the present graph, we observed smaller half-lives for the neutron number 2, 5, 12, 14, 16, 18, 20 and 26, which are near or equal to magic number of the nuclei.

We have also studied the logarithmic half-lives of different models such as Univ, NRDX, UDL, Horoi. Figure 4 describes the variation of logarithmic half-lives of different models such as Univ, NRDX, UDL, Horoi and present work with the mass number of cluster in the superhaevy region $^{299-302}$120 and it is

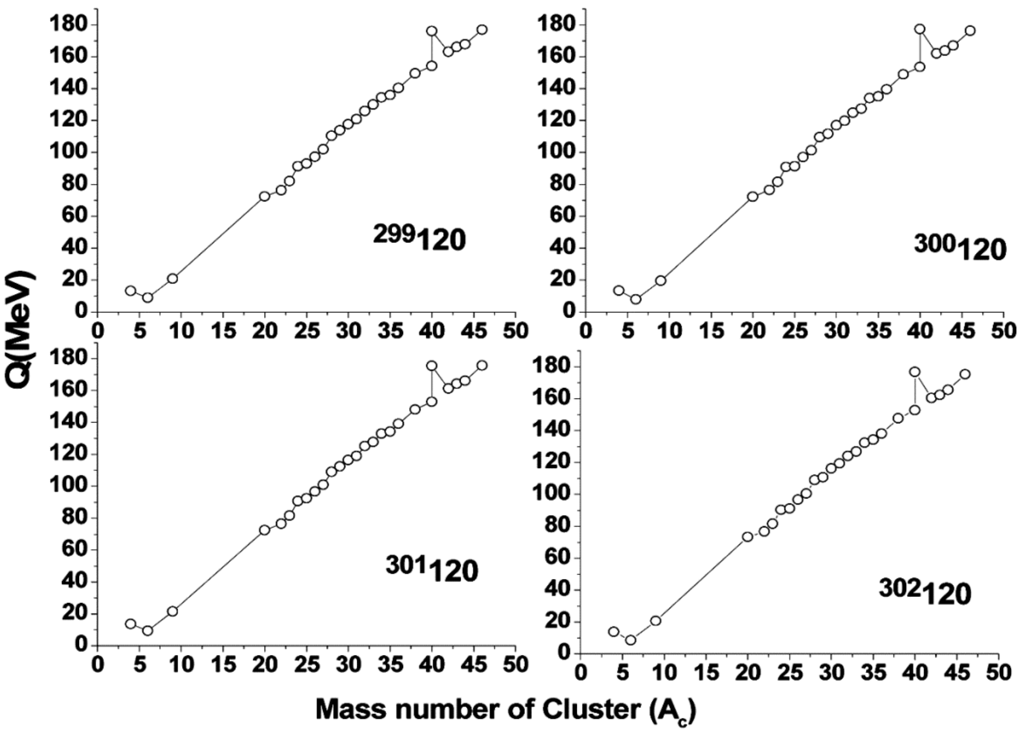

Fig. 1 – Variation of amount of energy released during cluster radioactivity with mass number of cluster (A_c) for the isotopes of superheavy nuclei $^{299-302}$120

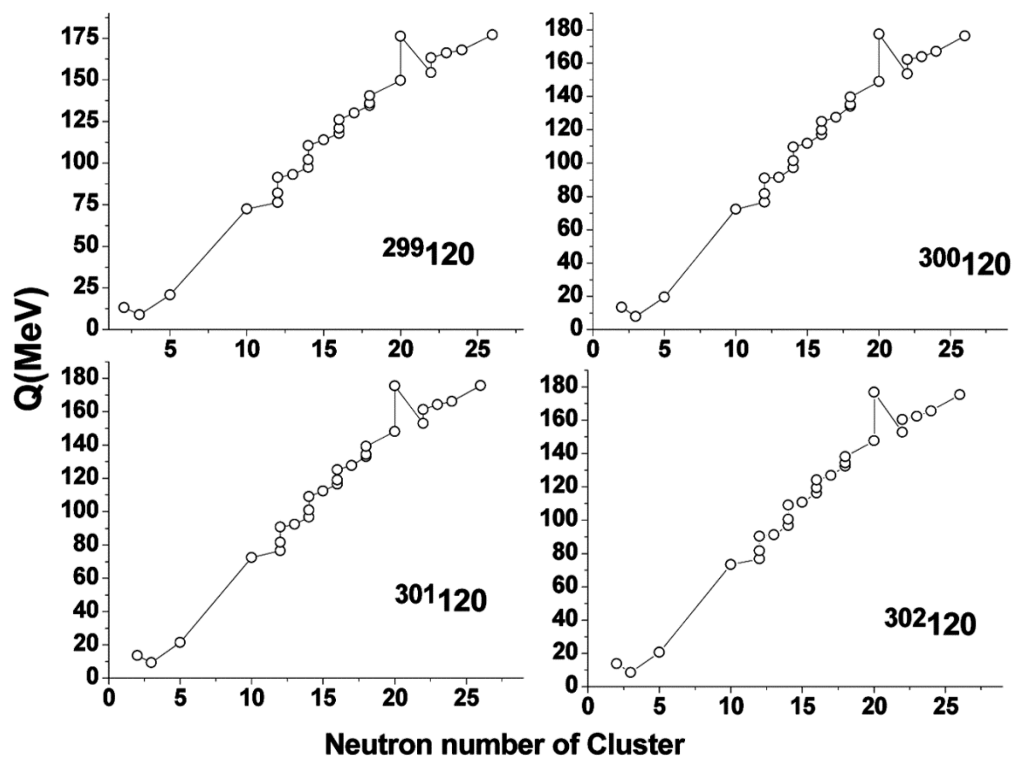

Fig. 2 – A Variation of amount of energy released during cluster radioactivity with the neutron number of cluster for the isotopes of superheavy nuclei $^{299-302}$120.

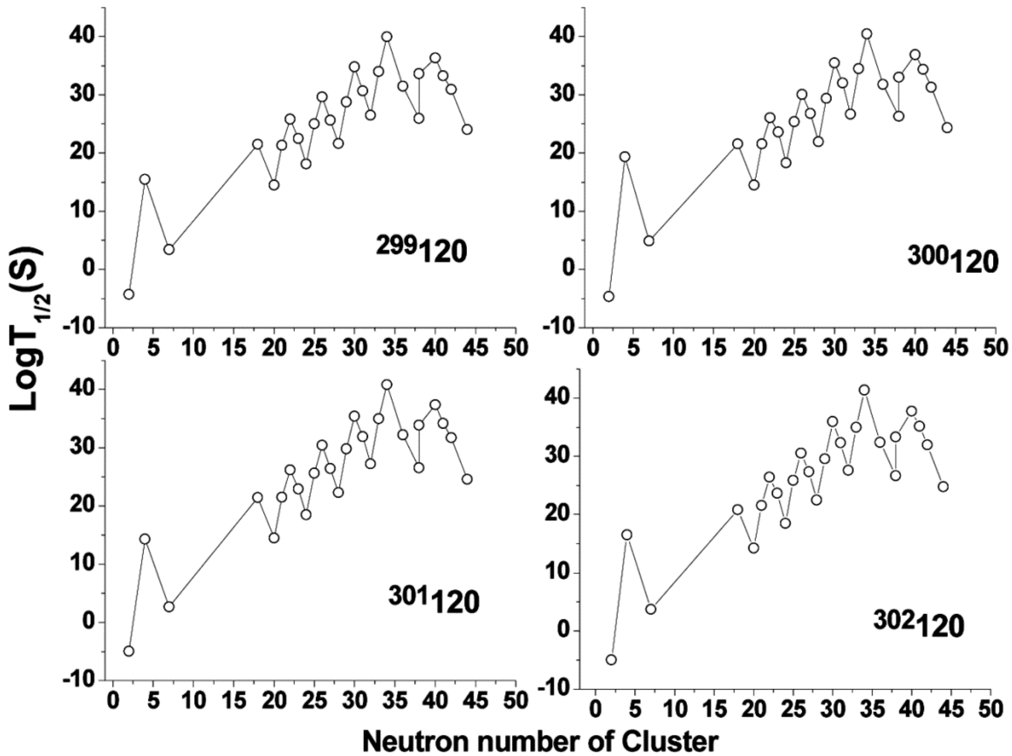

Fig 3 – A variation of logarithmic half-lives of cluster radioactivity with the neutron number of cluster for the isotopes of superheavy nuclei $^{299-302}120$.

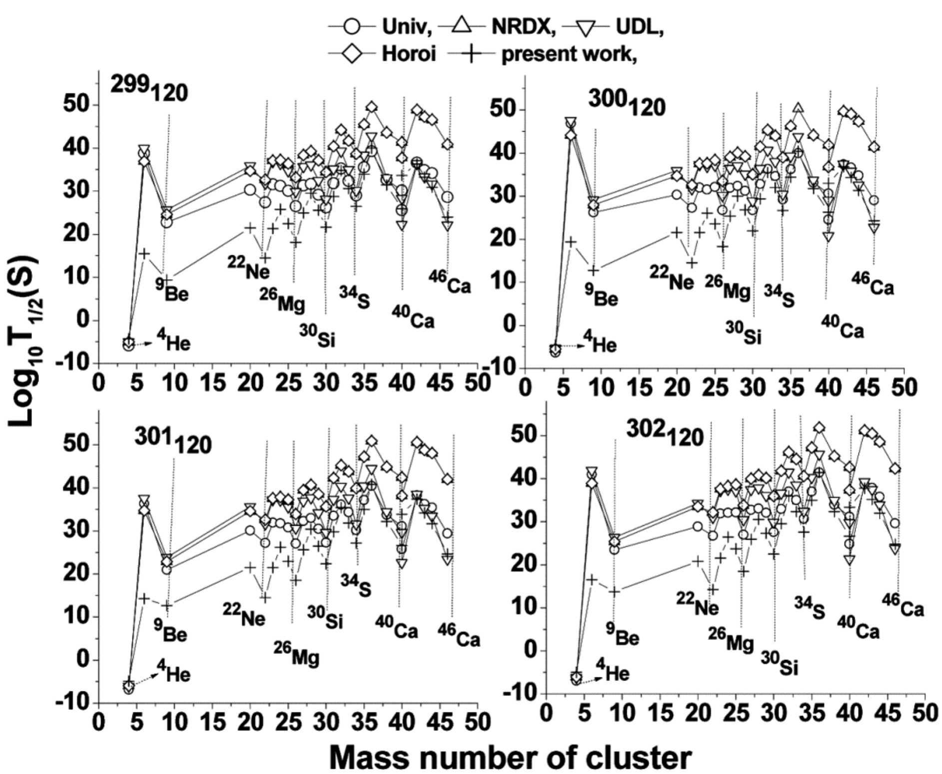

Fig. 4 – A comparison of logarithmic half-lives of different decay modes such as Univ, NRDX, UDL, Horoi and present work with the mass number of cluster for the isotopes of superheavy nuclei $^{299-302}120$.

presented in Fig. 4. From the figure we observed that the logarithmic half-lives of cluster emission such as ^{4}He, ^{9}Be, ^{22}Ne, ^{26}Mg, ^{30}Si, ^{34}S, ^{40}Ca and ^{46}Ca are having smaller half-lives compared to other cluster emission in the isotopes of superheavy nuclei $^{299\text{-}302}120$. From this study, it is found that the cluster decay half-lives are smaller for the cluster nuclei whose mass number or neutron numbers are nearer/equal to magic number. We have also studied the variation of logarithmic half-lives of cluster emission with the neutron number and we presented the same in Fig. 5. From the figure we have observed that as the mass number of cluster increases, the logarithmic half-life increases with the increase in neutron number. We have tabulated corresponding values of logarithmic half-lives and amount of energy released in the isotopes of superheavy nuclei $^{299\text{-}302}120$ are tabulated in Tables 1 and 2. From the tables and graphs, it is found that alpha decay (^{4}He) is having smaller half-lives compared to other cluster decay mode.

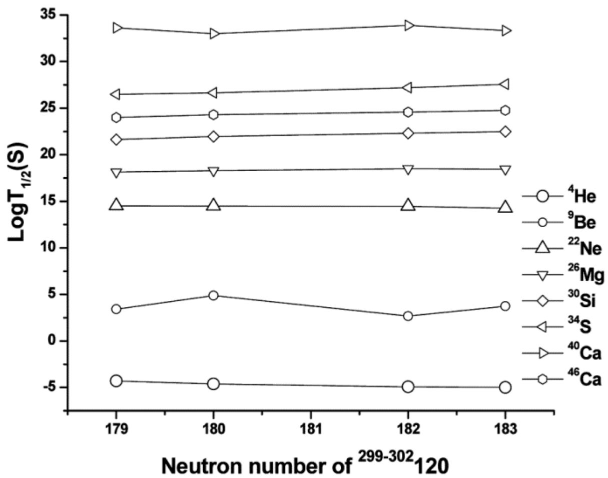

Fig. 5 – The variation of logarithmic half-lives of different clusters as a function of neutron number for the isotopes of superheavy nuclei $^{299\text{-}302}120$.

Table 1 – Tabulation of logarithmic half-lives of different cluster emission in the isotopes of superheavy nuclei $^{299\text{-}302}120$.

Cluster emission	Log $T_{1/2}$(S)			
	$^{299}120$	$^{300}120$	$^{301}120$	$^{302}120$
^{4}He	-4.303	-4.633	-4.931	-4.985
^{6}Li	15.496	19.367	14.292	16.545
^{9}Be	3.398	4.871	2.662	3.736
^{20}Ne	21.509	21.544	21.453	20.840
^{22}Ne	14.507	14.474	14.467	14.243
^{23}N	21.301	21.532	21.525	21.555
^{24}Mg	25.834	26.058	26.195	26.404
^{25}Mg	22.472	23.574	22.918	23.663
^{26}Mg	18.144	18.279	18.493	18.454
^{28}Si	25.004	25.391	25.622	25.888
^{29}Si	29.590	30.033	30.400	30.519
^{30}Si	25.630	26.806	26.429	27.341
^{31}P	21.630	21.960	22.315	22.485
^{32}S	28.785	29.370	29.812	29.550
^{33}S	34.816	35.482	35.392	35.948
^{34}S	30.652	32.019	31.870	32.339
^{35}Cl	26.475	26.649	27.198	27.570
^{36}Ar	33.982	34.449	34.994	34.966
^{38}Ar	39.980	40.465	40.788	41.397
^{40}Ar	31.475	31.788	32.185	32.402
^{40}Ca	25.957	26.271	26.573	26.669
^{42}Ca	33.634	32.999	33.887	33.332
^{43}Ca	36.351	36.862	37.389	37.747
^{44}Ca	33.247	34.351	34.154	35.156
^{45}Ca	30.887	31.291	31.696	31.978
^{46}Ca	24.002	24.308	24.582	24.770

Table 2 – The tabulation of amount of energy released during different cluster emission in the isotopes of superheavy nuclei $^{299\text{-}302}120$.

Cluster emission	Q(MeV)			
	$^{299}120$	$^{300}120$	$^{301}120$	$^{302}120$
^{4}He	13.105	13.395	13.665	13.715
^{6}Li	8.923	7.823	9.313	8.603
^{9}Be	20.792	19.612	21.422	20.512
^{20}Ne	72.384	72.334	72.463	73.342
^{22}Ne	76.361	76.415	76.427	76.797
^{23}N	82.049	81.692	81.703	81.657
^{24}Mg	91.301	90.951	90.738	90.414
^{25}Mg	93.188	91.38	92.45	91.237
^{26}Mg	97.276	97.03	96.642	96.712
^{28}Si	101.941	101.284	100.895	100.449
^{29}Si	110.484	109.735	109.122	108.923
^{30}Si	113.815	111.706	112.377	110.764
^{31}P	117.819	117.173	116.484	116.155
^{32}S	120.91	119.853	119.064	119.531
^{33}S	126.132	124.982	125.136	124.186
^{34}S	130.03	127.522	127.792	126.946
^{35}Cl	134.543	134.196	133.108	132.378
^{36}Ar	136.108	135.251	134.262	134.314
^{38}Ar	140.573	139.723	139.162	138.112
^{40}Ar	149.531	148.904	148.116	147.686
^{40}Ca	154.251	153.569	152.916	152.709
^{42}Ca	176.112	177.492	175.566	176.766
^{43}Ca	163.278	162.261	161.223	160.523
^{44}Ca	166.243	163.96	164.363	162.325
^{45}Ca	167.93	167.063	166.2	165.603
^{46}Ca	177.105	176.371	175.716	175.269

4 Conclusions

In summary, we have carried out the study of cluster radioactivity in the isotopes of superheavy nuclei $^{299\text{-}302}120$. We have studied logarithmic half-lives for the ground-to ground transitions in the emission of clusters such as ^{4}He, ^{6}Li, ^{9}Be, ^{20,22}Ne, ^{23}N, $^{24\text{-}26}$Mg, $^{28\text{-}30}$Si, ^{31}P, $^{32\text{-}34}$S, ^{35}Cl, ^{36,38,40}Ar, $^{40\text{-}46}$Ca. We have studied the amount of energy released and logarithmic half-lives in the super-heavy nuclei $^{299\text{-}302}120$. From this study, it is found that the cluster radioactivity half-lives are smaller for the cluster nuclei whose atomic or neutron number are nearer/equal to magic number. The present results are in good agreement with the other models such as Univ, NRDX, UDL and Horoi. From the outcomes of the present work, it emphasizes on the dependence of logarithmic half-lives and Q-values near or equal to the magic number. Hence, the superheavy nuclei $^{299\text{-}302}120$ are stable against the cluster decay and the dominant decay mode is ^{4}He (alpha decay). The present study on the superheavy nuclei $^{299\text{-}302}120$ finds an important role in the future experiments.

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