J. Nucl. Phys. Mat. Sci. Rad. A. Vol. 8, No. 1 (2020), pp.55–63

CHITKARA

Journal of Nuclear Physics, Material Sciences, Radiation and Applications

Journal homepage: https://jnp.chitkara.edu.in/

Cluster Radioactivity in Super-Heavy Nuclei $^{299\text{-}306}122$

H.C. Manjunatha[1], S. Alfred Cecil Raj[2], A.M. Nagaraja[1,2] and N. Sowmya[1,3]

[1]*Department of Physics, Government College for Women, Kolar-563101, Karnataka, India*

[2]*Department of Physics, St. Joseph's College, Tiruchirapalli-620002, Tamilnadu, India*

[3]*Deptartment of Physics, BMS Institute of Technology and Management, Bengaluru-560064, Karnataka, India*

[2]sac63raj@gmail.com
[1,2]amnagaraja@yahoo.com
[1,3]sowmyaprakash8@gmail.com
[1]manjunathhc@rediffmail.com (Corresponding Author)

ARTICLE INFORMATION

Received: August 28, 2020
Revised: October 07, 2020
Accepted: October 09, 2020
Published Online: November 09, 2020

Keywords:
Super-heavy Nuclei, Cluster Radioactivity

DOI: 10.15415/jnp.2020.81007

ABSTRACT

Cluster radioactivity is an intermediate process between alpha decay and spontaneous fission. It is also an exotic decay mode in super-heavy nuclei. When super-heavy nuclei undergo cluster decay, the daughter nuclei is having near or equal to doubly magic nuclei. We have investigated cluster decay of isotopes of He, Li, Be, Ne, N, Mg, Si, P, S, Cl, Ar and Ca in the super-heavy nuclei region $^{299\text{-}306}122$. We have also compared the logarithmic half-lives of cluster decay with that of other models such as Univ [1], NRDX [2], UDL [3] and Horoi [4]. From this study it is concluded that an alpha decay is the dominant decay mode in the superheavy nuclei $^{299\text{-}306}122$.

1. Introduction

Super-heavy elements are not natural elements. These super-heavy elements have to be synthesized and their synthesis plays a very dynamic role in the extension of the periodic table. Poenaru et al., [1] plotted single line universal curve both for alpha and cluster radioactivity by plotting the sum of decimal logarithm of the half-life and cluster preformation probability against the decimal logarithmic penetration probability. They considered fission theory for large mass asymmetry based on the quantum mechanical tunnelling process. Ni et al., [2] proposed NRDX formula by considering quantum tunnelling through the potential barrier. The half-lives were evaluated by using the preformation probability, which varies from one decay mode to another but does not significantly change for a given radioactivity. Qi et al., [3] presented universal decay formula by considering microscopic mechanism of the charged-particle emission. The half-lives were evaluated by using Q-values of the outgoing particles as well as the masses and charges of the nuclei involved in the decay. Horoi et al., [4] proposed independent model and analysed the accumulated data by pointing important variables in case of alpha and cluster decay of the even-even heavy nuclei.

Cluster emission, and decay from super-heavy elements leads to cluster radioactivity. Poenaru et al., [5-6] studied branching ratios and half-lives in the super-heavy region. Ismail and Seif [7] studied half-lives of cluster ^{14}C, ^{20}O, ^{20}Ne and ^{24}Ne in heavy and super-heavy nuclei region. Zang et al., [8] evaluated half-lives of heavy and super-heavy nuclei using WKB approximation. Zhang and Wang [9] studied cluster and alpha decay in the isotopes of super-heavy nuclei ^{294}118, ^{296}120 and ^{298}122. Wang et al., [10] studied preformation probability using generalised liquid drop model. Zagrebaev et al., [11] studied ternary fission in doubly magic nuclei of tin. Ismail et al., [12] studied alpha decay half-lives in the super-heavy nuclei. Shanmugam et al., [13] studied alpha decay chains in the super-heavy region Z=114-116 and 118. Previous workers [14-15] studied alpha decay half-lives of super-heavy region using generalized liquid-drop model (GLDM) and density-dependent cluster model.

Agbemava et al., [16] theoretically studied the properties such as charge radii and neutron skins of the hyperheavy nuclei using density functional theory. Cui et al., [17] studied alpha decay half-lives with in the frame of the effective liquid drop model (ELDM). Previous workers

ISSN No.: 2321-8649(Print) ISSN No.: 2321-9289(Online); Registration No. : CHAENG/2013/51628

[18-20] estimated the alpha decay half-lives in the super-heavy region using generalised density dependent model. The alpha decay half-lives of spherical and deformed nuclei for the study of nuclear structure of super-heavy elements was reported by earlier workers [21-22]. Matheson et al., [23] reported dependence of Q value on cluster emissions. Warda et al., [24] predicted a sharp fission fragment mass distribution with the heavy fragment close to ^{208}Pb. Karim and Ahmed [25] investigated alpha decay half-lives in the super-heavy nuclei Z=120. Routray et al., [26] evaluated half-lives using WKB integral method in the very heavy nuclei region.

Earlier workers [27-44] studied different decay modes such as spontaneous fission, ternary fission, cluster decay and alpha decay in the heavy and super-heavy region and also predicted suitable projectile-target combinations to synthesize these super-heavy nuclei. Karpeshin [45] has shown that the choice of a specific shape of the proximity potential affects not only the shape of the barrier, but can also change the total kinetic energy of fragments by tens of MeV. From the available literature it is witnessed that the cluster decay plays a very important role in identifying the existence of the super-heavy nuclei.

Extensive theoretical and experimental search for cluster emission from various heavy and super-heavy nuclei ranging from ^{14}C to ^{80}Ge [46-49] have been studied. The present study focus on the cluster decay such as ^{4}He, ^{22}Ne, ^{26}Mg, ^{28,30}Si, ^{34}S, ^{40}Ca and ^{46}Ca which are magic nuclei or near the magic nuclei whose half-lives are maximum. The hypothetical super-heavy nuclei such as Z=120, 122 124 and 126 are most predictable super-heavy nuclei in the island of stability. From the literature [50] it is observed that the super-heavy nuclei $^{299\text{-}306}$122 survives fission. In order to check whether, the isotopes of Z=122 also survives the cluster decay such as Li, Be, Ne, N, Mg, Si, P, S, Cl, Ar and Ca, we made an attempt to study different cluster decay in the super-heavy nuclei region of $^{299\text{-}306}$122 by using proximity potential 2013. The overlap between the two nuclei increases, the proximity potential model becomes more complex due to the nuclear potential interacting within the shorter distance of the nuclear surfaces. Hence in the present work we have used the DFM with the density-dependent nucleon-nucleon interaction and studied nuclear potential with the universal function (Prox13) [51].

The present paper is organised as follows. The Sec II consists of theory for the present model and semi-empirical formulae

2. a. Theory

The total interacting potential is the sum of the coulomb potential and proximity potential and it is studied using the following equation;

$$V(R) = V_N(R) + V_C(R) \tag{1}$$

The interaction with atom is given by

$$V_C(r) = Z_1 Z_2 e^2 \begin{cases} \dfrac{1}{R} & (R > R_C) \\ \dfrac{1}{2R_C}\left[3 - \left(\dfrac{R}{R_C}\right)^2\right] & (R < R_C) \end{cases} \tag{2}$$

where Z_1 and Z_2 are the atomic number of emitted cluster/alpha particle and daughter nuclei. $R_C = 1.24 \times (R_1 + R_2)$ where R_1 and R_2 are the radii of the emitted alpha/cluster and daughter nuclei respectively. The proximity potential is based on proximity force theorem [52]. The nuclear proximity potential is given by

$$V_P(Z) = 4\pi\gamma\bar{R}\Phi\left(\frac{z}{b}\right) \tag{3}$$

where z is the distance between the near surfaces of the fragments, and b is the nuclear surface thickness (b=0.99). where Φ is the universal proximity potential which depends on the minimum separation distance and is independent of geometry and shape of the nuclei. The surface tension co-efficient is given by $\gamma = 1.25284 \left[1 - 2.345 \left(N - Z/A\right)^2\right]$ MeV/fm^2. The mean curvature is given by $\bar{R} = C_1 C_2 / C_1 + C_2$ where C_1 and C_2 are the sussmann's central radius of cluster/alpha nuclei and daughter nuclei respectively. The Sussmann central radii C_1 and C_2 are related to sharp radii R_i and it is expressed as $C_i = R_i - \left(b^2/R_i\right)$. The sharp radii R_i is written as $R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}$. The proximity function specially defined for cluster/alpha decay is as follows;

$$\Phi(s_0) = \frac{p_1}{1 + \exp\left(\dfrac{s_0 + p_2}{p_3}\right)} \tag{4}$$

The constants p_1=−7.65, p_2=1.02 and p_3=0.89. The S_0 is evaluated from the equation $s_0 = R - R_1 - R_2/b$ where R, R_1 and R_2 are the radii of parent, daughter and emitted cluster. The half-lives of the cluster decay can also be evaluated by using Hill-Wheeler formalism, since the coulomb intercation is not included in the formalism [53] we have evaluated the cluster decay half-lives using WKB integral;

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_2}^{R_3} \sqrt{2\mu(V_T(r) - Q)}\,dr\right\} \tag{5}$$

where μ is the reduced mass of the fission fragments. R_a and R_b are the initial and finishing turning points, and it can be evaluated as $V_T(R_a) = Q = V_T(R_b)$. The half-life of the cluster decay is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{\upsilon P} \quad (6)$$

where $\upsilon = \frac{\omega}{2\pi} = \frac{2E_v}{h}$ represent assaults frequency and λ is the decay constant. E_v is the empirical vibration energy and expressed as;

$$E_v = Q\left\{0.056 + 0.039\exp\left[\frac{4-A_2}{2.5}\right]\right\} \text{ for } A_2 \geq 4. \quad (7)$$

2. b. Comparison of Prox 13 with the other Models:

i. UNIV Formula: Poenaru et al., [1] derived single line of universal (UNIV) curve for alpha and cluster decay by plotting the sum of the decimal logarithm of the half-life and cluster preformation probability versus the decimal logarithm of the penetrability of external barrier. This formula is referred as UNIV formula it is expressed as,

$$\log T_{1/2}^{UNIV} = -\log P_S - 22.169 + 0.598(A_e - 1) \quad (8)$$

Where $-\log P_S = c_{AZ}\left[\arccos\sqrt{r} - \sqrt{r(1-r)}\right]$ with $c_{AZ} = 0.22873(\mu_A Z_d Z_e R_b)^{1/2}$, $r = R_t/R_b$, $R_b = 1.43998$ $Z_d Z_e/Q$ and $\mu_A = A_d A_e/A$

ii. NRDX formula: Ni et al., [2] derived semi-empirical formula for alpha and cluster decay half-lives from the WKB barrier penetration probability with certain approximations. The proposed formula is

$$\log T_{1/2}^{NRDX} = a\sqrt{\mu}Z_\alpha Z_d Q^{-1/2} + b\sqrt{\mu}(Z_\alpha Z_d)^{1/2} + c \quad (9)$$

where a, b, and c are fitting coefficients and corresponding values are 6.8, 6.9 and −22.4 respectively. This is referred as NRDX in the present work.

iii. Universal Decay Law (UDL): Qi et al., [3] presented a linear universal decay formula from the microscopic mechanism of the charged-particle emission. It relates the half-lives of monopole radioactive decays with the Q values of the outgoing particles as well as the masses and charges. This formula is used in the calculation of half-lives of alpha decay and cluster decay.

$$\log T_{1/2}^{UDL} = aZ_c Z_d A^{1/2} Q^{-1/2} + b\left(AZ_c Z_d\left[A_d^{1/3} + A_c^{1/3}\right]\right)^{1/2} + c \quad (10)$$

where $A = \sqrt{A_c A_d/(A_c + A_d)}$

where a, b, and c are fitting coefficients and corresponding values are 0.3949, -0.3693 and -23.7615 respectively.

iv. Horoi et al. formula: Horoi et al., [4] proposed scaling law for the decay time of alpha particles and it is generalized for cluster decay. They proposed that $\log T_{1/2}$ depends linearly on the scaling variable $(Z_c Z_d)^{0.6}/Q_c$ and on the square root of the reduced mass of cluster and daughter.

$$\log T_{1/2}^{H} = \left(a_1\sqrt{\mu} + b_1\right)\left[(Z_\alpha Z_d)^y Q^{-1/2} - 7\right] + \left(a_2\sqrt{\mu} + b_2\right) \quad (11)$$

here the fitting constants a_1=6.8, b_1=-7.5, a_2=6.9 and b_2=−22.4

3. Results and Discussions

The amount of energy released from the cluster decay such as ^{4}He, ^{6}Li, ^{9}Be, ^{12}C, ^{14}N, ^{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 studied using mass excess values available in the reference [54]. The Figure 1 shows the variation of scattering potential with the mass number of clusters. From the figure it is observed that as the mass number of cluster increases scattering potential also increases. The studied scattering potential of ^{6}Li, ^{9}Be, ^{22}Ne, ^{26}Mg, ^{28,30}Si, ^{34}S, and ^{40,46}Ca in the isotope of super-heavy element ^{299}122 with the variant of separation distance between the two nuclei is presented in Figure 2. From the figure it has been examined that the driving potential for ^{299}122 varies between 80MeV to 184MeV during the cluster emission of ^{22}Ne and ^{46}Ca respectively.

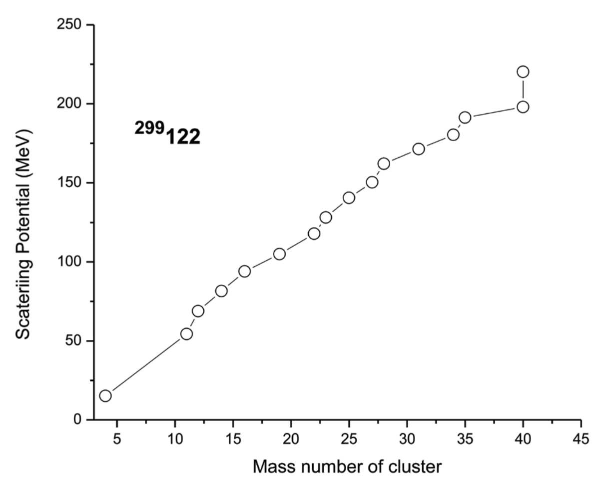

Figure 1: A variation of scattering potential with the mass number of clusters.

In order to show the variation of scattering potential, we have considered negative separation between the two nuclei. For an instance, let us consider the total scattering potential as function of separation distance between the two nuclei is as shown in Figure 3 during an alpha emission from the nuclei ^{299}122. It is observed that the total scattering potential consists of three classical turning points such as R_1, R_2 and R_3. The WKB integral by using equation (5) is evaluated using the first boundary condition i.e $V(R_2)=Q$ is close to origin and second boundary condition $V(R_3)=Q$ which is away from the origin. Hence the total scattering potential helps us to analyse the half-lives. These half-lives are inversely proportional to the penetration probability and it is evaluated using the WKB integral. If the penetration probability is more, then the corresponding half-lives were small.

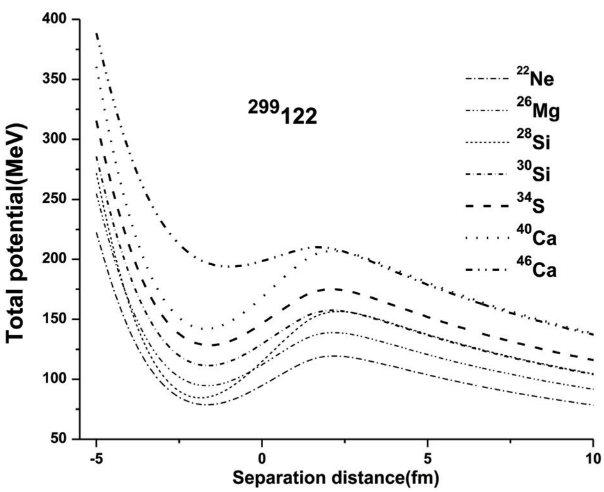

Figure 2: The variation of total potential with the separation distance between the fission fragments in the cluster decay of super-heavy element ^{299}122.

We have also studied half-lives of different cluster emission using driving potential and penetration probability in the super-heavy nuclei $^{299-306}$122 using the equations (1) to (6). The half-life values of Prox 13 compared with the different models such as Univ [1], NRDX [2], UDL [3] and Horoi [4] Figures 4 shows the variation of logarithmic half-lives of Prox 13 and different models such as Univ, NRDX, UDL Horoi with the mass number of clusters. The half-lives of the cluster emission of ^{4}He, ^{6}Li, ^{9}Be, ^{22}Ne, ^{26}Mg, ^{28,30}Si, ^{34}S, and ^{40,46}Ca are calculated for the super-heavy nuclei $^{299-306}$122. Among all the studied clusters, alpha decay has minimum half-lives. Earlier workers [6] have observed unexpected results. They predict that the half-lives of cluster radioactivity (T_c) are smaller compared to alpha decay half-lives. But the present study contradicts the earlier work. We obtained that $T_\alpha < T_c$ by using available mass excess values [54]. Thus, we took into account that the half-lives are sensitive to the amount of energy released. Half-lives of cluster emission using the Prox 13 is compared with that of the other model such as Univ, NRDX, UDL and Horoi and it is also presented in Table 1. The values obtained using the present model is close to the UNIV model.

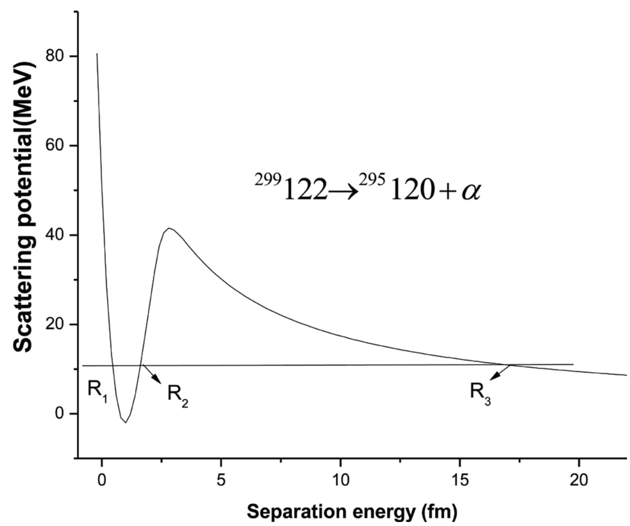

Figure 3: The variation of scattering potential with the separation distance between fission fragments in the alpha-decay of super-heavy element ^{299}122.

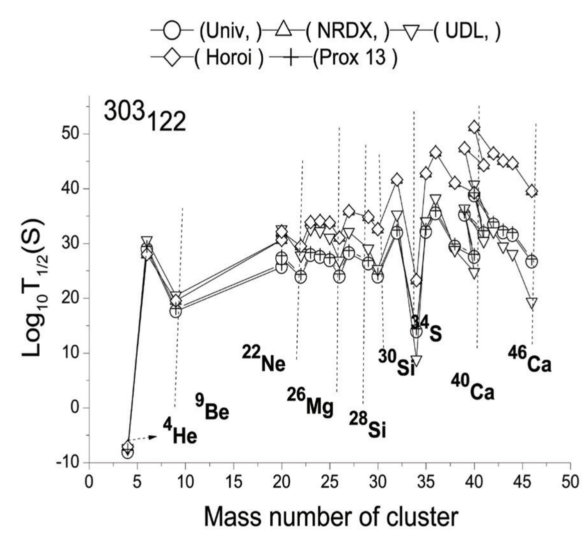

Figure 4: Comparison of logarithmic half-lives of present work with the Univ, NRDX, UDL, Horoi in the super-heavy element $^{303-306}$122.

Table 1: A comparison of different cluster emissions (^{4}He, ^{6}Li, ^{9}Be, ^{22}Ne, ^{26}Mg, $^{28,30}Si$, ^{34}S, and $^{40,46}Ca$) half-lives of Prox 13 with the different models such as, NRDX, UDL, Horoi and Univ.

Parent nuclei	Cluster emission	Half-lives(s)				
		Prox 13	NRDX	UDL	Horoi	UNIV
$^{299}122$	^{4}He	-5.506	-7.775	-7.542	-5.446	-7.506
	^{6}Li	26.793	28.484	25.949	25.529	26.793
	^{9}Be	18.149	21.045	19.973	19.973	18.149
	^{22}Ne	22.501	26.111	27.857	22.801	22.502
	^{26}Mg	21.535	23.787	28.364	16.167	21.535
	^{28}Si	12.752	6.983	21.582	9.158	12.752
	^{30}Si	20.971	21.384	29.267	19.330	20.971
	^{34}S	23.698	23.083	33.502	24.033	23.698
	^{40}Ca	25.693	22.161	36.973	24.061	34.660
	^{46}Ca	25.561	17.633	37.888	22.923	24.561
$^{300}122$	^{4}He	-5.893	-6.063	-6.009	5.571	-6.893
	^{6}Li	36.621	37.901	34.745	35.330	34.621
	^{9}Be	22.695	25.668	24.439	24.286	22.695
	^{22}Ne	23.471	27.281	28.881	13.312	23.471
	^{26}Mg	22.561	25.097	29.470	16.751	22.561
	^{28}Si	14.188	9.236	23.334	10.049	14.188
	^{30}Si	21.820	22.530	30.220	19.856	21.820
	^{34}S	24.755	24.544	34.670	24.705	24.755
	^{40}Ca	26.568	23.430	37.989	24.626	36.265
	^{46}Ca	26.009	18.334	38.493	23.250	26.009
$^{301}122$	^{4}He	-6.754	-5.914	-5.863	-4.333	-5.625
	^{6}Li	31.618	33.130	30.320	30.912	30.504
	^{9}Be	19.301	22.230	21.167	20.848	21.410
	^{22}Ne	24.217	28.176	29.680	30.709	29.939
	^{26}Mg	23.580	26.387	30.560	28.326	30.770
	^{28}Si	13.744	22.551	22.913	21.829	22.201
	^{30}Si	22.938	24.025	31.439	20.531	31.767
	^{34}S	25.328	25.334	35.340	25.086	35.487
	^{40}Ca	27.068	24.152	38.607	24.967	38.021
	^{46}Ca	26.413	18.963	39.045	23.547	39.369
$^{302}122$	^{4}He	-5.027	-6.199	-6.103	5.507	-6.642
	^{6}Li	40.100	41.217	37.879	17.037	37.314
	^{9}Be	22.438	25.417	24.258	4.204	24.545
	^{22}Ne	24.204	28.167	29.733	13.732	29.344
	^{26}Mg	23.888	26.781	30.940	17.524	30.624
	^{28}Si	14.723	10.072	24.124	10.442	18.328
	^{30}Si	23.620	24.934	32.210	20.956	30.384
	^{34}S	25.799	25.980	35.904	25.408	34.780
	^{40}Ca	27.476	24.742	39.134	25.255	37.334
	^{46}Ca	26.690	19.394	39.461	23.766	37.689

ISSN No.: 2321-8649(Print) ISSN No.: 2321-9289(Online); Registration No. : CHAENG/2013/51628

$^{303}122$	^{4}He	-5.618	-7.117	-7.355	-7.117	-8.251
	^{6}Li	29.446	27.979	30.572	27.979	27.765
	^{9}Be	18.090	19.556	20.489	19.556	17.897
	^{22}Ne	24.382	29.483	27.789	29.330	23.882
	^{26}Mg	28.013	34.076	32.236	32.544	27.515
	^{28}Si	24.435	31.061	26.845	30.498	23.934
	^{30}Si	26.834	34.834	29.053	31.765	26.334
	^{34}S	24.407	32.581	25.318	30.682	23.907
	^{40}Ca	40.408	23.279	28.816	23.415	28.908
	^{46}Ca	27.986	39.246	24.764	39.753	27.486
$^{304}122$	^{4}He	-5.804	-7.279	-7.551	-7.203	-8.305
	^{6}Li	33.350	31.493	34.318	31.708	32.850
	^{9}Be	20.497	21.950	22.952	20.840	19.997
	^{22}Ne	23.768	28.944	27.061	25.582	23.267
	^{26}Mg	27.885	34.021	32.083	33.705	27.384
	^{28}Si	24.207	30.908	26.567	29.342	23.707
	^{30}Si	28.346	36.382	30.989	35.634	27.847
	^{34}S	24.455	32.710	25.387	31.636	23.954
	^{40}Ca	15.253	24.334	20.127	24.957	14.754
	^{46}Ca	28.212	29.579	25.093	29.433	27.712
$^{305}122$	^{4}He	-5.004	-7.453	-7.762	-7.124	-8.504
	^{6}Li	26.685	25.550	27.920	25.911	26.185
	^{9}Be	16.049	17.606	18.396	17.497	15.548
	^{22}Ne	23.176	28.423	26.356	28.665	22.676
	^{26}Mg	27.553	33.780	31.691	32.389	27.053
	^{28}Si	24.013	30.788	26.328	30.584	23.512
	^{30}Si	27.158	35.312	29.483	35.061	26.660
	^{34}S	24.617	32.954	25.609	31.408	24.117
	^{40}Ca	14.567	23.637	19.072	23.435	14.068
	^{46}Ca	28.260	39.730	25.170	35.483	27.761
$^{306}122$	^{4}He	-5.003	-7.439	-7.759	-7.397	-8.503
	^{6}Li	31.941	30.286	32.979	31.305	31.441
	^{9}Be	17.732	19.305	20.134	19.489	17.233
	^{22}Ne	22.360	27.679	25.380	27.817	21.860
	^{26}Mg	26.572	32.918	30.507	32.648	26.072
	^{28}Si	23.595	30.447	25.810	30.502	23.093
	^{30}Si	28.236	36.435	30.860	36.634	27.735
	^{34}S	24.494	32.914	25.453	32.788	23.994
	^{40}Ca	15.290	24.551	10.193	24.450	14.790
	^{46}Ca	28.130	39.698	24.993	39.100	27.631

Conclusions

We have studied driving potential, amount of energy released, penetration probability and half-lives for the super-heavy nuclei $^{299-306}$122. We have also compared Prox 13 results with the Univ, NRDX, UDL and Horoi. The cluster emission of ^{4}He, ^{6}Li, ^{9}Be, ^{22}Ne, ^{26}Mg, ^{28,30}Si, ^{34}S, and ^{40,46}Ca in super-heavy nuclei $^{299-306}$122, it is evident that the cluster radioactivity is possible only when a daughter or cluster nuclei are nearly magic or doubly magic nuclei. In the present work, it is observed that the alpha decay is the dominant decay mode in the super-heavy nuclei $^{299-306}$122.

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Journal of Nuclear Physics, Material Sciences, Radiation and Applications

Chitkara University, Saraswati Kendra, SCO 160-161, Sector 9-C, Chandigarh, 160009, India

Volume 8, Issue 1 **August 2020** **ISSN 2321-8649**