Predictions of Heavy Cluster Emission from Z = 122, 123 and 124 Superheavy Elements

P. Deneshan[1], K. Prathapan[1], and R. K. Biju[1,2,*]
[1]*Department of Physics, Govt.Brennan College, Thalassery,-670106, INDIA*
[2]*Department of Physics, Pazhassi Raja N S S College, Mattanur- 670702, INDIA*
* *email: bijurkn@gmail.com*

Introduction

Over the past few decades, theoretical and experimental research on the structure, synthesis, and decay characteristics of superheavy elements has advanced significantly. Spontaneous fission, alpha decay, and cluster radioactivity are some of the decay modes of superheavy nuclei. In cluster radioactivity, particles heavier than alpha particles are emitted from the nucleus and was predicted by Sandulescu, Poenaru, and Greiner [1] in 1980. In 2018, the possibility for the emission of heavy clusters with Z > 28 was predicted Poenaru et al. [2], which changed the concept of cluster decay. The emission of such heavy clusters is characterized by the fact that and the daughter nuclei are ^{208}Pb or the neighboring ones which shows the importance of shell effects in determining the decay properties of superheavy elements. Some isotopes of superheavy elements up to Z = 118 were synthesized through fusion reactions and attempts are being made to synthesize higher elements.

Methodology

After the prediction of Poenaru et al. [2], many other theoretical studies reported the possibility of heavy cluster decays from superheavy elements. In the same year Zhang and Wang [3] used some empirical formulae to study the cluster radioactivity of superheavy elements and reported that the Universal Decay Law (UDL) of Qi et al. [4] suggests that the heavy cluster decay as the preferred decay mode in superheavy nuclei. Santhosh et al. [5] also studied the heavy cluster decay from SHE using the Coulomb and Proximity Potential Model (CPPM) and verified the predictions of Poenaru et al. [3].

Recently, in 2021, our group investigated the dependence of decay half-life on the Q-value, charge and mass asymmetries and surface area of the cluster and proposed an empirical formula exclusively for determining the decay half-lives of clusters with Z > 20 from superheavy nuclei. The formula (PB formula) is given as [6];

$$\log_{10} T_{1/2} = a\left(Z_d - Z_c\right)\frac{Z_c}{Z_d}Q^{-1/2} + bA_c^{2/3} + c \qquad (1)$$

The half-life is expressed in seconds and the coefficients for various types of clusters are given in ref. 6.

In the present study, we investigate the possible heavy cluster decays from superheavy elements using our new empirical formula and the results are compared with the predictions of UDL which is given as [4]:

$$\log_{10} T_{1/2} = \begin{Bmatrix} aZ_cZ_d\sqrt{\mu}Q_c^{-1/2} \\ +b\sqrt{\mu Z_c Z_d\left(A_c^{1/3} + A_d^{1/3}\right)} + c \end{Bmatrix} \qquad (2)$$

The coefficients are taken from ref. 4.

Results and Discussion

Possible heavy cluster emissions from $^{289\text{-}330}$122, $^{292\text{-}330}$123, $^{296\text{-}330}$124 superheavy elements were studied using our new empirical formula. The Q-values are calculated using the expression,

$$Q = \begin{Bmatrix} \Delta M_p - \left(\Delta M_d + \Delta M_c\right) \\ +10^{-6}k\times\left(Z_p^\beta - Z_d^\beta - Z_c^\beta\right) \end{Bmatrix} \qquad (3)$$

which includes the corrections for screening effect of orbital electrons. The mass excess values are calculated using the WS4 mass table. We have investigated the possibility for the heavy cluster emission from 116 isotopic nuclei of the selected Z- values. Even though the preferred modes of decay in superheavy region are the alpha decay and spontaneous fission, we could find some possible heavy cluster emissions from superheavy elements with decay half-lives well within the experimental limits. The results of our calculations are compared with the predictions of the Universal Decay Law. Results of our calculations for Z = 124 are given in table 1.

Table 1: Possible heavy cluster emissions from Z = 124 superheavy nuclei calculated by using the PB formula and UDL.

Parent	Cluster	Q-Value (MeV)	$\log_{10} T_{1/2}(s)$	
			PB	UDL
^{318}124	^{83}Nb	342.0	-2.95	-5.22
^{319}124	^{83}Nb	340.3	-1.94	-2.85
^{321}124	^{83}Nb	336.3	0.36	-1.33
^{322}124	^{83}Nb	334.1	1.67	1.46
^{323}124	^{83}Nb	331.9	2.95	2.19
^{324}124	^{83}Nb	329.5	4.33	4.15
^{325}124	^{83}Nb	327.4	5.57	5.85
^{326}124	^{82}Mo	340.6	-4.37	-3.22
^{326}124	^{83}Nb	325.6	6.65	7.29
^{327}124	^{83}Nb	323.6	7.87	8.98
^{327}124	^{82}Mo	338.7	-4.29	-2.78
^{328}124	^{82}Mo	337.1	-3.34	-0.57
^{328}124	^{83}Nb	321.4	9.25	10.9

From the table it is clear that for the decays presented, the decay half-lives are well below the experimental upper limit of 10^{30} seconds and above the experimental lower limit of 10^{-6} seconds. Other superheavy nuclei with Z = 122 and 123 also showed significant probability for the emission of heavy clusters.

In the next part of our study, we have calculated the spontaneous fission (SF) and alpha decay half-lives of all the isotopes considered above to analyze the competition between probable decays. The alpha decay half-lives are calculated using the Universal Decay Law and the spontaneous fission half-lives are calculated using the formula of Santhosh et al. [6]. It is given as;

$$\log_{10} T_{1/2} = \left\{ \begin{array}{l} a\dfrac{Z^2}{A} + b\left(\dfrac{Z^2}{A}\right)^2 + c\left(\dfrac{N-Z}{N+Z}\right) \\ +d\left(\dfrac{N-Z}{N+Z}\right)^2 + eE_{shell} + f \end{array} \right\} \quad (3)$$

where the SF half-lives are expressed in years and the coefficients are taken from ref. 6. The calculated values of SF and alpha decay half-lives of Z = 124 nuclei are plotted in figure 1.

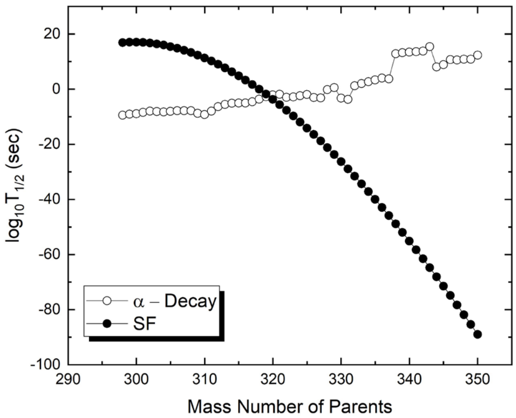

Fig 1: Plot of alpha decay and SF half-lives verses the mass number of parents for Z = 124

From the plot it is clear that up to A = 319, the alpha decay dominates and after that the dominant decay mode is the spontaneous fission. On comparison with the data given in table 1, it can be seen that for A = 318, 319 326, 327 and 328, the heavy cluster decay half-lives are lower than the alpha decay and SF half-lives and are within the experimental lower limit. This clearly indicates that the dominant mode of these nuclei could be the heavy cluster decay. For the isotopes of Z = 122 and 123 also we could find some possible heavy cluster emissions with half-lives comparable to or even less than that of alpha decay and spontaneous fission.

References

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