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Heavy Cluster Radioactivity and other Decay Modes of Superheavy Element ^{306}120

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ABSTRACT

Background: Many theoretical studies and experimental attempts are conducted to synthesize SHN with Z =120 being an element with a proton magic number. The prediction of the island of stability also encourages scientists to search for the existence of super heavy nuclei near Z=120.

Purpose: Main aim of our work is to predict all heavy cluster emissions from superheavy nuclei (SHN) ^{306}120.

Methods: Modified Generalized Liquid drop model (MGLDM) with Q value dependent pre-formation factor [*Phys. Rev. C*, 99, 064604 (2019)] is the theoretical model used to calculate the alpha and cluster decay half-life of SHN ^{306}120. The spontaneous fission half-life is predicted using the shell effect and mass inertia dependent formula by our group [*Phys. Rev. C*, 104, 024617 (2021)].

Results: We investigate all cluster emissions from ^{306}120, and the fragment combination ^{123}Cd (Z=48) leading to ^{183}Hf daughter nucleus is predicted to be a probable heavy cluster decay with half-lives comparable with alpha decay half-lives. The heavy cluster ^{137}Xe (N=83) with ^{169}Dy daughter nucleus is predicted to be the most probable cluster decay with the least half-life among all fragment combinations. Thus, our study shows the role of the magic number of proton and neutron in cluster decay. We also predict that the superheavy element ^{306}120 decays by 4 alpha chains followed by spontaneous fission.

Conclusions: The predicted half-life in the case of alpha decay and heavy cluster emission from SHN ^{306}120 are within experimental limits and we hope that our predictions will guide future experiments.

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1. Introduction

Superheavy elements are the trans-actinide elements introduced in 1958 [1] as the synonyms for elements that exist only due to nuclear shell effects. In recent years researchers have given great attention to study the synthesis, decay and identification of superheavy nuclei (SHN). To date, superheavy elements upto Og (Z=118) have been experimentally synthesized through hot fusion [2] and cold fusion reactions [3]. Attempts to synthesis superheavy elements with Z =119 and 120 [4, 5] are in progress. In an effort to synthesise the new superheavy element with Z = 120, Hofmann et al. [5] examined the reaction ^{54}Cr + ^{248}Cm to study its production and decay properties.

The shell closure effects enable SHN to exist regardless of the high Coulomb repulsion in the superheavy region. The predictions on the island of stability which enable enhanced stability in superheavy regions due to shell closure, urge scientists to conduct experiments to identify elements near predicted magic numbers. Most modern calculations predict closed proton shells at Z=114, 120, 124 or 126 and a neutron shell closure at N=172 or 184 [6-10]. The superheavy nuclei ^{306}120, an isotope with proton magic number (Z=120) and near neutron magic number with N=186, is an element of utmost importance among researchers. In this present work, we aim to make a detailed study on all possible heavy cluster decay from superheavy nuclei ^{306}120 so as to confirm whether long-lived elements could exist around magic numbers Z=120 and N=184.

Present work is organized as follows. In Section 2, we have given the theoretical framework of the Modified Generalized Liquid Drop Model (MGLDM) and in Section 3 we have given the formula for spontaneous fission half-life which is used in this work. Section 4 provides the calculations performed and explains the conclusive results we obtained based on calculations. Finally, Section 5 contains the summary of the entire work.

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2. Modified Generalized Liquid Drop Model (MGLDM)

The total energy for a deformed nucleus in MGLDM is the sum of volume energy, surface energy, Coulomb energy, nuclear proximity energy and rotational energy and is given by,

$$E = E_V + E_S + E_C + E_P + E_R. \tag{1}$$

The terms E_V, E_S, E_C, E_P and E_R represent the volume, surface, Coulomb, proximity and rotational energy terms, respectively. In our present work, we have not considered the rotational energy term E_R because the angular momentum (ℓ) value involved in the decay process is very small ($\approx 5\hbar$) and its contribution to half-life is very small [11].

For the pre-scission region [12],

$$E_V = -15.494(1-1.8I^2)A, \tag{2}$$

$$E_S = 17.9439(1-2.6I^2)A^{2/3}\left(S/4\pi R_0^2\right), \tag{3}$$

$$E_C = 0.6e^2(Z^2/R_0) \times 0.5\int (V(\theta)/V_0)(R(\theta)/R_0)^3 \sin\theta d\theta. \tag{4}$$

Here I, S, $V(\theta)$ and V_0 represents the relative neutron excess, surface of the deformed nucleus, electrostatic potential at the surface and surface potential of the sphere respectively.

The effective sharp radius of the parent nucleus, R_o is defined as

$$R_0 = 1.28A^{1/3} - 0.76 + 0.8A^{-1/3} \tag{5}$$

For the post-scission region [12],

$$E_V = -15.494\left[(1-1.8I_1^2)A_1 + (1-1.8I_2^2)A_2\right], \tag{6}$$

$$E_S = 17.9439\left[(1-2.6I_1^2)A_1^{2/3} + (1-2.6I_2^2)A_2^{2/3}\right], \tag{7}$$

$$E_C = \frac{0.6e^2Z_1^2}{R_1} + \frac{0.6e^2Z_2^2}{R_2} + \frac{e^2Z_1Z_2}{r}. \tag{8}$$

Here A_i, Z_i, R_i and I_i are the masses, charges, radii and relative neutron excess of the fragments, r is the distance between the centers of the fragments.

The nuclear proximity potential E_p is given by Blocki et al., [13] as,

$$E_p(z) = 4\pi\gamma b\left[\frac{C_1C_2}{(C_1+C_2)}\right]\Phi\left(\frac{z}{b}\right), \tag{9}$$

With γ the nuclear surface tension coefficient and Φ represents the universal proximity potential [14],

$$\gamma = 0.9517[1-1.7826(N-Z)^2/A^2]\,\text{MeV/fm}^2, \tag{10}$$

where N, Z and A represent neutron, proton and mass number of parent nucleus respectively.

The barrier penetrability P is calculated using

$$\mathrm{P} = \exp\left\{-\frac{2}{\hbar}\int_{R_{in}}^{R_{out}} \sqrt{2B(r)[E(r)-E(sphere)]}\,dr\right\}, \tag{11}$$

where $R_{in} = R_1 + R_2, B(r) = \mu$ and $R_{out} = e^2Z_1Z_2/Q$. R_1, R_2, μ and Q represents the radius of the daughter nuclei, radius of emitted cluster, the reduced mass and the released energy respectively. $E(r)$ is the deformation energy given by eqn. (1) and E (sphere) is the spherical liquid drop energy. The partial half-life is related to the decay constant λ by

$$T_{1/2} = \left(\frac{\ln 2}{\lambda}\right) = \left(\frac{\ln 2}{\nu P_C P}\right), \tag{12}$$

Assault frequency ν depends on zero point vibrational energy and we have taken it as $10^{20}\,s^{-1}$. In cluster radioactivity [15,16], both alpha and heavy cluster decay obey the universal plot of $\log_{10}T_{1/2}$ vs. –lnP with same slope and intercept which indicate that both alpha and cluster decay have same assault frequency.

The preformation factor [17] is given as

$$P_C = 10^{aQ+bQ^2+c}, \tag{13}$$

With a= −0.25736, b=6.37291 x 10^{-4}, c=3.35106 and Q is the Q value or the energy released in a radioactive nuclear reaction.

3. The formula for spontaneous fission (SF) half-life

The SF half-lives are predicted using the mass inertia parameter $\left(I_{rigid}\right)$ dependent SF formulae by Santhosh et al.,[18] and are given below:

$$\log_{10}[T_{1/2}(yr)] = c_1 + c_2\left(\frac{Z^2}{(1-kI^2)A}\right) + c_3\left(\frac{Z^2}{(1-kI^2)A}\right)^2 + c_4E_{shell} + c_5I_{rigid} + h_i. \tag{14}$$

Where $I_{rigid} = B_{rigid}[1+0.31\beta_2+0.44\beta_2^2+....]$ is rigid body mass inertia of a nucleus [19, 20] with the mass parameter, $B_{rigid} = \frac{2}{5}MR^2 = 0.0138A^{5/3}(\hbar^2/MeV)$ and $R = 1.2A^{1/3}(fm)$. Here M, β_2 are mass of the nucleus and the quadrupole deformation respectively. The value of constants are c_1 = 1208.763104, c_2 = -49.26439288, c_3 = 0.486222575, c_4 = 3.557962857, c_5 = 0.04292571494 with fixed value of k = 2.6 [21] and h_i is blocking effect for unpaired nucleon. For even-even heavy and superheavy nuclei $h_i = 0$, for odd N nuclei, h_{eo} = 2.749814 and for odd Z nuclei, h_{oe} = 2.490760.

4. Results and Discussion

A systematic study on all possible heavy particle emissions from superheavy nuclei with magic proton numbers Z=120 and A=306 has been analyzed within the MGLDM with Q value-dependent preformation factor. The Modified Generalized liquid drop model (MGLDM) is the theoretical model proposed by Santhosh et al.,[17] by adding proximity potential developed by Blocki et al., [13] to the model GLDM of Royer [12, 22]. The study includes the evaluation of all possible cluster daughter combinations possible for ^{306}120 with a positive Q value. The Q value of the decay process is computed using the expression

$$Q = \Delta M_p - (\Delta M_d + \Delta M_c), \tag{15}$$

ΔM_p, ΔM_d and ΔM_c are the masses of parent nuclei, daughter nuclei and cluster, respectively. The masses are taken from ref. [23] and those nuclei whose experimental values are not available are taken from KTUY05[24].

For our study, we have taken into account only those fragment combinations with predicted half-life values that lie well within the experimental limit (less than 10^{30}s) and branching ratio down to 10^{-19}.The branching ratio is calculated using the formula,

$$b = \frac{\lambda_{cluster}}{\lambda_\alpha} = \frac{T_{1/2}^{\alpha}}{T_{1/2}^{cluster}}, \tag{16}$$

Where $\lambda_{cluster}$, λ_α, $T_{1/2}^{\alpha}$ and $T_{1/2}^{cluster}$ are the cluster emission decay constant, alpha emission decay constant, alpha decay half-life and cluster decay half-life, respectively.

Figure 1 represents the variation of logarithm of probable heavy cluster decay half-life vs. mass number of cluster. It should be noted that as cluster size increases, half-life shows a decreasing trend. Also, one could notice a few peaks and dips in predicted heavy cluster decay half-life. The peak in half-life corresponds to the stability of the parent nucleus, and the dip corresponds to the stability of decay fragments. Radioactive decay is more probable to occur when the decay fragments are stable with closed shells. In figure some examples of small dip in half-life corresponds to fragment combinations [^{94}Sr+^{212}Pb (Z=82)], [^{96}Sr+^{210}Pb (Z=82)], [^{100}Zr+^{206}Hg (N=126)], [^{110}Ru+^{196}Os (N=120)], [^{126}Sn (Z=50) +^{180}Yb]. From the mentioned results, the role of the magic number of protons or neutrons in shell closure and stability is obvious.

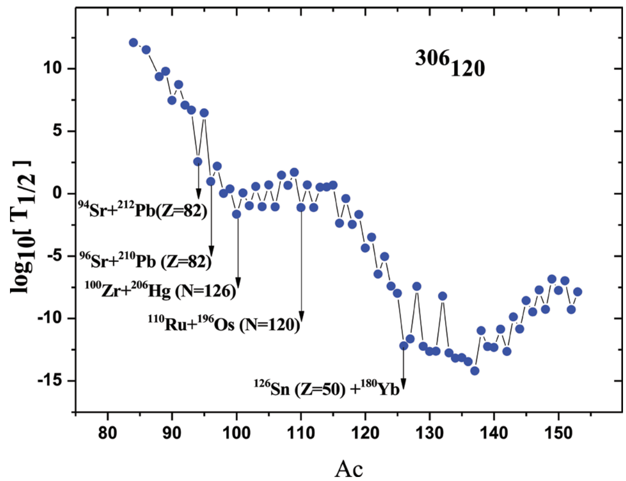

Figure 1: Plot of the computed $\log_{10}T_{1/2}$ values vs. cluster size for probable heavy cluster decay from ^{306}120.

The predicted heavy cluster decays possible from ^{306}120 within the experimental limit are shown in Table 1. Column 1-6 represents the parent nuclei, probable heavy cluster, daughter nuclei, Q value, heavy cluster decay half-life, and branching ratio. According to the concept of heavy particle radioactivity by Poenaru et al.,[25], there are cases where the chances for heavy particle decay are more probable than alpha decay. In our present study, it should be noted that selenium (Z=34) is the lightest heavy cluster that may be emitted from superheavy nuclei. The predictions by Poenaru et al., [25] that heavy clusters with Z>28 will be emitted from superheavy nuclei with Z>110 support our findings. One of the peculiar features of heavy cluster radioactivity is that either the predicted heavy cluster or daughter nuclei will be highly stable due to the closed shell effect. From the table, one may notice heavy cluster decays from ^{306}120, with half-life comparable to alpha decay half-life and the decay with minimum half-life among all fragment combinations possible. The fragment combination ^{123}Cd (Z=48) with ^{183}Hf daughter is predicted to be a probable heavy cluster decay with a half-life $\left(T_{1/2}^{cluster} = 9.17\times10^{-6}s\right)$ comparable with alpha decay half-life $\left(T_{1/2}^{\alpha} = 1.10\times10^{-6}s\right)$. The heavy cluster ^{137}Xe (N=83) with ^{169}Dy daughter nucleus is predicted to be the most probable cluster decay with the least half-life $\left(T_{1/2}^{cluster} = 6.23\times10^{-15}s\right)$ among all fragment combinations. The main interesting point of our study is the confirmation of the importance of the magicity of proton and neutron number in heavy cluster decay from SHN. We hope our work will be a good suggestion for experimentalists to focus on these heavy cluster decays from $^{306}120$ as they are more probable to occur than other decays.

Table 1: Table denotes the probable heavy cluster decay from $^{306}120$ within the experimental limits. The heavy cluster with half-life comparable with alpha half-life, and cluster with minimum half-life are highlighted.

Parent nuclei	Probable cluster	Daughter nuclei	Q value (MeV)	$T_{1/2}^{cluster}(s)$	Branching ratio
$^{306}120$	^{4}He	^{302}Og	13.2251	1.10E-06	
	^{84}Se	^{222}Rn	285.3055	1.23E+12	8.93E−19
	^{86}Se	^{220}Rn	285.6211	3.28E+11	3.35E−18
	^{88}Kr	^{218}Po	297.0644	2.34E+09	4.70E−16
	^{89}Kr	^{217}Po	296.3818	6.21E+09	1.77E−16
	^{90}Kr	^{216}Po	298.9068	2.94E+07	3.74E−14
	^{91}Kr	^{215}Po	297.2457	5.59E+08	1.96E−15
	^{92}Kr	^{214}Po	298.9693	1.21E+07	9.05E−14
	^{93}Rb	^{213}Bi	303.5820	4.87E+06	2.25E−13
	^{94}Sr	^{212}Pb	312.1245	3.61E+02	3.04E−09
	^{95}Rb	^{211}Bi	303.4800	2.89E+06	3.80E−13
	^{96}Sr	^{210}Pb	313.3825	9.15E+00	1.20E−07
	^{97}Sr	^{209}Pb	311.9256	1.55E+02	7.08E−09
	^{98}Sr	^{208}Pb	313.9016	1.05E+00	1.05E−06
	^{99}Y	^{207}Tl	317.4140	2.39E+00	4.59E−07
	^{100}Zr	^{206}Hg	323.0530	2.23E-02	4.92E−05
	^{101}Zr	^{205}Hg	321.1840	1.15E+00	9.59E−07
	^{102}Zr	^{204}Hg	322.0081	1.10E-01	1.00E−05
	^{103}Nb	^{203}Au	323.9020	3.71E+00	2.96E−07
	^{104}Mo	^{202}Pt	328.7720	9.10E-02	1.21E−05
	^{105}Mo	^{201}Pt	326.8070	4.97E+00	2.21E−07
	^{106}Mo	^{200}Pt	328.4640	8.59E-02	1.28E−05
	^{107}Mo	^{199}Pt	325.6707	3.02E+01	3.63E−08
	^{108}Mo	^{198}Pt	326.3900	4.54E+00	2.42E−07
	^{109}Tc	^{197}Ir	328.2770	5.16E+01	2.13E−08
	^{110}Ru	^{196}Os	334.0830	7.55E-02	1.45E−05
	^{111}Ru	^{195}Os	332.0250	5.11E+00	2.15E−07
	^{112}Ru	^{194}Os	333.7961	7.67E-02	1.43E−05
	^{113}Rh	^{193}Re	334.7280	3.24E+00	3.39E−07
	^{114}Ru	^{192}Os	331.8342	3.36E+00	3.27E−07
	^{115}Rh	^{191}Re	334.3100	4.74E+00	2.32E−07
	^{116}Pd	^{190}W	339.9420	4.21E-03	2.61E−04
	^{117}Pd	^{189}W	337.7740	4.04E-01	2.72E−06
	^{118}Pd	^{188}W	339.7867	3.47E-03	3.17E−04
	^{119}Ag	^{187}Ta	341.2760	2.10E-02	5.23E−05

^{120}Cd	^{186}Hf	346.1070	4.25E-05	2.58E−02
^{121}Cd	^{185}Hf	345.1238	3.22E-04	3.41E−03
^{122}Cd	^{184}Hf	347.8424	3.63E-07	3.02E+00
^{123}Cd	**^{183}Hf**	**346.4242**	**9.17E-06**	**1.20E−01**
^{124}Cd	^{182}Hf	348.4817	3.90E-08	2.81E+01
^{125}In	^{181}Lu	351.0070	1.02E-08	1.08E+02
^{126}Sn	^{180}Yb	356.3450	6.55E-13	1.68E+06
^{127}Sn	^{179}Yb	355.7410	2.30E-12	4.77E+05
^{128}In	^{178}Lu	350.2178	3.69E-08	2.97E+01
^{129}Sb	^{177}Tm	357.8290	5.98E-13	1.84E+06
^{130}Te	^{176}Er	359.7129	2.24E-13	4.91E+06
^{131}Te	^{175}Er	359.5910	2.37E-13	4.63E+06
^{132}I	^{174}Ho	357.1230	6.16E-09	1.78E+02
^{133}I	^{173}Ho	360.9380	1.73E-13	6.35E+06
^{134}I	^{172}Ho	361.2530	6.67E-14	1.65E+07
^{135}Xe	^{171}Dy	362.3330	7.23E-14	1.52E+07
^{136}Te	^{170}Er	360.2640	3.48E-14	3.15E+07
^{137}Xe	**^{169}Dy**	**363.7134**	**6.23E-15**	**1.76E+08**
^{138}Cs	^{168}Tb	361.3370	1.06E-11	1.04E+05
^{139}Xe	^{167}Dy	361.3046	5.52E-13	1.99E+06
^{140}Xe	^{166}Dy	361.3013	4.74E-13	2.32E+06
^{141}Ba	^{165}Gd	361.9130	1.36E-11	8.07E+04
^{142}Ba	^{164}Gd	363.3420	2.29E-13	4.80E+06
^{143}Ba	^{163}Gd	360.9810	1.30E-10	8.48E+03
^{144}Ba	^{162}Gd	361.7770	1.41E-11	7.78E+04
^{145}La	^{161}Eu	360.3570	2.68E-09	4.09E+02

Decay chains of SHN ^{306}120 are predicted by comparing α decay half-life with SF half-lives. Alpha decay half-lives are calculated using the model MGLDM, and the SF half-lives are predicted using the mass inertia parameter $\left(I_{rigid}\right)$ dependent SF formulae by Santhosh et al.,[18]. Those superheavy nuclei with alpha decay half-life values less than spontaneous fission half-lives will undergo alpha decay. From our calculations in Table 2, we insist that the isotope ^{306}120 will survive fission and decays to ^{302}Og through alpha decay. Then our study predicts that the nuclei ^{302}Og decay to ^{298}Lv, which again decays to ^{294}Fl through alpha decay. Thus, in the decay chain of ^{306}120, the alpha decay half-life is less than the spontaneous fission half-life for the first four consecutive cases. We predict that the superheavy nuclei ^{306}120 decay by four alpha chains followed by spontaneous fission.

Table 2: Table denotes the decay modes of ^{306}120.

Parent Nuclei	Q_α (MeV)	$T_{1/2}^{SF}\left(s\right)$	$T_{1/2}^{\alpha}\left(s\right)$	Mode of decay
^{306}120	13.2251	8.63E-06	1.10E-06	α
^{302}Og	10.9151	6.28E+01	5.30E-02	α
^{298}Lv	10.2651	3.61E+05	7.64E-01	α
^{294}Fl	8.4951	8.32E+06	9.21E+04	α
^{290}Cn	8.1351	3.45E+01	4.02E+05	SF

5. Conclusion

We have estimated all possible chances of heavy cluster decay from SHN $^{306}120$ using MGLDM with Q value dependent preformation factor. The cluster decay with half-life comparable to that of alpha decay half-life, and with minimum half-life among all decay is found to have either magic number of proton or neutron. Our results have revealed the importance of the magicity of proton and neutron number in radioactive decay of superheavy nuclei. Most of the half-life predicted is within the experimental limit. Therefore, we guess that our study will motivate experimentalists to conduct future experiments in the field of super heavy nuclei.

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Nil

Authorship contribution

Tinu Ann Jose: Participated in design, data computation and drafting the paper.
K. P. Santhosh: Participated in design, guidance and final approval of the paper.
N. K. Deepak: Participated in design and data analysis of the paper.

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Conflict of Interest

The authors declare that they have no known financial or personal relationship that could have appeared to influence the work reported in the paper.

Declaration

It is an original data and has neither been sent elsewhere nor published anywhere.

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