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Prediction of Decay Modes for Superheavy Nuclei with Magic Number of Neutrons and Protons

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Abstract

The Cubic plus Yukawa plus Exponential (CYE) model has been used to study the different decay properties of Superheavy nuclei $^{298,310}114$, $^{306,318}122$, $^{308,310}124$, $^{310,322}126$ and compared them with the available theoretical and experimental values. Here, the half-lives of several clusters have been computed that have not yet been detected experimentally. Hopefully, this will assist future research in this area. As a result of comparing the three different decay modes (α-decay, cluster radioactivity and spontaneous fission), it was possible to predict the predominant decay modes of Superheavy nuclei.

Keywords: Alpha decay; Cluster decay, Spontaneous fission, Superheavy nuclei; Magic numbers.

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1. Introduction

In Nuclear and Atomic Physics, the search for Superheavy nuclei brought significant change. Superheavy research has become much more active during the past few decades due to extensive experimental investigations and supporting theoretical analysis. More than thirty Superheavy nuclei have been synthesized using cold and hot fusion reactions [1-5]. Research on the decay modes of Superheavy nuclei is important because newly formed isotopes are confirmed by observing their decay properties. As a result, the half-lives of radioactive decays are used as experimental indicators for Superheavy nuclei production. Different attempts have been made to synthesize the Superheavy elements Z > 118 with a wide variety of projectiles, such as Sc, Ti, V, Cr, Mn, Fe and Co [6,7]. By a variety of decay modes, these Superheavy elements which are rich in protons are split into fission fragments. Mostly, Superheavy elements undergo decay through alpha decay and spontaneous fission [8-10]. Apart from binary and alpha fission, Superheavy nuclei can undergo cluster

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radioactivity and ternary fission [11-14]. In the study of phenomena like alpha decay, double alpha decay, proton decay, cluster decay and spontaneous fission, several theoretical models have been employed [15-20].

The cubic plus Yukawa plus exponential model (CYEM) [21] in two-sphere approximation has been developed to study such different decay modes, in which zero-point vibration energy is explicitly foreseen without breaking the conservation of energy, and in which nuclear inertia mass coefficient as a function of centre of mass distance, is considered. Based on this model, we have already calculated the half-lives of alpha decay and cluster decay [22-24] for various isotopes of Superheavy elements with and without deformation effects. Here, we carried out our calculations for α-decay, cluster radioactivity (CR) and spontaneous fission (SF) half-lives of predicted Superheavy nuclei with magical numbers of protons and neutrons $^{298,310}114$, $^{306,318}122$, $^{308,310}124$ and $^{310,322}126$ using our realistic CYE model and are described in section 2.

2. Our Model

To study the logarithmic half-lives of Superheavy nuclei, the alpha decay, cluster decay and spontaneous fission process are investigated using the following theoretical framework. The potential V(r) is considered as the sum of the Coulomb potential, nuclear potential and the nuclear deformations,

$$V(r) = V_c(r) + V_n(r) - V_{df}(r) - Q; \quad r \geq r_t$$

For a prolate spheroidal daughter nucleus with a longer axis along the fission direction, Pik-Pichak [25] obtained,

$$V_c(r) = \frac{3}{2}\frac{Z_1 Z_2 e^2 \gamma}{r}\left[\frac{1-\gamma^2}{2}\ln\frac{\gamma+1}{\gamma-1} + \gamma\right]$$

For an oblate spheroidal daughter with a shorter axis along the fission direction,

$$V_c(r) = \frac{3}{2}\frac{Z_1 Z_2 e^2}{r}\left[\gamma\,(1+\gamma^2)\arctan\gamma^{-1} - \gamma^2\right]$$

The potential for the overlapping region is given by a third-order polynomial in r suggested by Nix [26] having the form,

$$V(r) = -E_v + [V(r_t) + E_v]\left\{s_1\left[\frac{r-r_i}{r_t-r_i}\right]^2 - s_2\left[\frac{r-r_i}{r_t-r_i}\right]^3\right\}; \quad r_i \leq r \leq r_t$$

Where,

$r_t = a_2 + R_1$

Here, a_2 is the semi-major or minor axis of the spheroidal cluster depending on the prolate or oblate shape of the emitted cluster; and r_i is the distance between the centers of mass of the daughter and the emitted particle portions in the spheroidal parent nucleus.

If the nuclei have a spheroid shape, the radius vector R(θ) making an angle θ with the axis of symmetry locating the sharp surface of deformed nuclei is given as [27]

$$R(\theta) = R_0\left[1 + \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\beta_{nm}Y_{nm}(\theta)\right]$$

Here R_0 is the radius of the equivalent spherical nucleus.

Expressing the energies in MeV, lengths in fm and time in seconds, for calculating the lifetime of the decay system we use the formula

$$T = \frac{1.433\times10^{-21}}{E_v}[1 + \exp(K)]$$

The action integral K is given by

$K = K_L + K_R$

Where, $K_L = \frac{2}{\hbar}\int_{r_a}^{r_t}[2B_r(r)V(r)]^{1/2}dr$

and $K_R = \frac{2}{\hbar}\int_{r_t}^{r_b}[2B_r(r)V(r)]^{1/2}dr$

The limits of integration r_a and r_b are the two appropriate zeros of the integrand which are found numerically.

3. Comparison of Different Decay Modes

In this work, using CYE model we have tried to study the half-lives for the predicted SHN ^{298,310}114, ^{306,318}122, ^{308,310}124 and ^{310,322}126 during the cluster emission such as ^{4}He, ^{9}Be, ^{11}B, ^{12}C, ^{14}N, ^{16}O, ^{19}F, ^{20}Ne, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{31}P, ^{34}S, ^{35}Cl, ^{40}Ar, ^{39}K and ^{40}Ca. The results of our study have been compared with those of available theoretical values [28-32] and are tabulated in Table 1. Using the mass excess values available in References [33-35], we have calculated the Q-values for different decay modes. The calculated half lifetime values are in good agreement with the other theoretical values. Furthermore, Our results also suggested that the predominant modes of decay are based on the logarithmic half-lives of Superheavy nuclei in Table 1. It is clear from the table that the three Superheavy nuclei ^{306}122, ^{308}124 and ^{310}126 undergoes alpha decay only.

Table 1. Comparison of the predicted half lifetime values for different decay modes (α-decay, cluster decay and SF) of Superheavy nuclei with the magical numbers.

Decays	Models		log $T_{1/2}$							
			^{298}Fl	^{310}Fl	^{306}122	^{318}122	^{308}124	^{310}124	^{310}126	^{322}126
α-decay	CPP-ITM [28]		-	-	-8.92(s)	0.43(s)	-	-9.20(s)	- 11.50(s)	-7.35(s)
	CPPM [31]		-	-	-8.11(s)	13.11(s)	-	-	-	-
	UDL [29]		5.41(s)	-	-9.01(s)	0.87(s)	-	-9.14(s)	-	-7.13(s)
	Royer [30]		5.87(s)	-	-8.25(s)	1.13(s)	-	-8.40(s)	-	-6.43(s)
	CYE(WOD)		4.20 (s)	9.20(s)	-7.93(s)	1.21(s)	-9.39(s)	-9.72(s)	-10.2(s)	-0.69(s)
	CYE(WPD)		-	9.16(s)	-	1.07(s)	-	-	-	-
	CYE(WPC)		-	-	-	-	-	-	-	-
Spontaneous Fission	Xu emp. Formula [39]		- 29.88(s)	-78.26(s)	9.91(s)	-20.7(s)	21.50(s)	-4.72(s)	33.93(s)	12.15(s)
	Ren emp. Formula [40]		- 40.11(s)	-120.8(s)	0.18(s)	-71.1(s)	11.00(s)	- 55.18(s)	21.63(s)	-38.4(s)
	CYEM		- 54.44(s)	2.11(s)	3.85(s)	-2.87(s)	35.21(s)	- 22.12(s)	15.17(s)	-30.1(s)
	^{11}B	CYE(WOD)	54.69(s)	49.03(s)	19.80(s)	10.94(s)	16.37(s)	14.32(s)	13.83(s)	52.84(s)
		CYE(WPD)	51.64(s)	48.84(s)	18.05(s)	-	14.91(s)	14.29(s)	9.55(s)	-
		CYE(WPC)	-	-	-	-	-	-	-	-
	^{12}C	CPPM [31, 32]	-	-	12.31(s)	29.28(s)	-	-	9.54(s)	24.73(s)
		UNIV [31]	-	-	-	-	-	-	6.97(s)	18.12(s)
		CYE(WOD)	39.84 (s)	20.74(s)	11.29(s)	35.06(s)	8.22(s)	7.29(s)	5.64(s)	34.53(s)
		CYE(WPD)	39.76 (s)	-	9.90(s)	38.60(s)	7.25(s)	7.84(s)	1.81(s)	-
		CYE(WPC)	33.96 (s)	16.30(s)	7.50(s)	29.28(s)	4.93(s)	4.18(s)	29.12(s)	28.63(s)
	^{14}N	CYE(WOD)	63.45(s)	64.75(s)	24.68(s)	51.40(s)	20.24(s)	18.50(s)	16.78(s)	48.50(s)
		CYE(WPD)	63.68(s)	-	21.80(s)	55.75(s)	17.99(s)	18.06(s)	12.33(s)	-
		CYE(WPC)	-	-	-	-	-	-	-	-

	^{16}O	CYE(WOD)	47.90(s)	49.76(s)	17.58(s)	37.04(s)	13.50(s)	12.32(s)	10.26(s)	34.20(s)
		CYE(WPD)	48.26(s)	49.47(s)	15.14(s)	-	12.00(s)	12.81(s)	6.17(s)	-
		CYE(WPC)	42.74(s)	44.26(s)	15.32(s)	34.93(s)	11.79(s)	12.62(s)	5.43(s)	25.65(s)
	^{19}F	CYE(WOD)	58.59(s)	58.56(s)	15.19(s)	43.09(s)	21.81(s)	20.28(s)	17.80(s)	38.26(s)
		CYE(WPD)	59.12(s)	-	15.49(s)	-	22.08(s)	20.05(s)	12.95(s)	-
		CYE(WPC)	47.62(s)	47.41(s)	6.05(s)	34.24(s)	12.73(s)	11.31(s)	7.36(s)	25.15(s)
	^{20}Ne	CYE(WOD)	61.76(s)	65.77(s)	29.08(s)	46.55(s)	22.29(s)	20.88(s)	17.71(s)	38.85(s)
		CYE(WPD)	62.25(s)	-	29.37(s)	-	19.15(s)	20.29(s)	12.44(s)	-
		CYE(WPC)	47.88(s)	51.48(s)	16.15(s)	33.63(s)	9.12(s)	7.28(s)	4.49(s)	23.43(s)
	^{23}Na	CYE(WOD)	63.29(s)	62.63(s)	32.60(s)	46.43(s)	26.00(s)	24.99(s)	20.61(s)	37.62(s)
		CYE(WPD)	63.83(s)	-	33.06(s)	-	26.33(s)	28.61(s)	14.99(s)	-
		CYE(WPC)	47.30(s)	46.47(s)	17.12(s)	30.59(s)	10.26(s)	8.80(s)	5.18(s)	20.68(s)
	^{24}Mg	CYE(WOD)	68.23(s)	71.18(s)	34.70(s)	51.14(s)	27.77(s)	27.19(s)	21.48(s)	39.95(s)
		CYE(WPD)	68.71(s)	-	35.40(s)	-	28.15(s)	31.21(s)	15.41(s)	-
		CYE(WPC)	51.27(s)	53.80(s)	18.97(s)	35.34(s)	11.75(s)	10.64(s)	5.45(s)	21.98(s)
	^{27}Al	CYE(WOD)	67.67(s)	69.26(s)	37.21(s)	51.32(s)	30.25(s)	29.44(s)	24.01(s)	40.47(s)
		CYE(WPD)	68.35(s)	-	37.92(s)	-	31.02(s)	33.81(s)	17.68(s)	31.92(s)
		CYE(WPC)	49.75(s)	51.13(s)	23.48(s)	35.27(s)	17.60(s)	16.91(s)	13.17(s)	25.99(s)
	^{28}Si	CYE(WOD)	73.35(s)	77.74(s)	39.45(s)	56.17(s)	32.06(s)	31.72(s)	25.57(s)	43.86(s)
		CYE(WPD)	73.96(s)	-	40.10(s)	-	32.76(s)	36.74(s)	18.79(s)	-
		CYE(WPC)	53.82(s)	57.82(s)	24.34(s)	38.28(s)	18.08(s)	17.80(s)	13.59(s)	27.74(s)
	^{31}P	CYE(WOD)	76.01(s)	53.59(s)	42.47(s)	59.80(s)	35.61(s)	36.35(s)	29.92(s)	47.67(s)
		CYE(WPD)	76.80(s)	-	43.56(s)	55.04(s)	36.79(s)	41.58(s)	23.09(s)	33.162(s)
		CYE(WPC)	57.25(s)	-	26.45(s)	41.13(s)	20.56(s)	20.96(s)	16.57(s)	32.24(s)
	^{34}S	CYE(WOD)	65.33(s)	68.29(s)	35.57(s)	52.07(s)	29.33(s)	30.58(s)	24.14(s)	41.94(s)
		CYE(WPD)	66.42(s)	58.04(s)	37.20(s)	48.92(s)	31.08(s)	36.29(s)	18.29(s)	28.81(s)
		CYE(WPC)	44.58(s)	47.17(s)	19.10(s)	32.32(s)	14.21(s)	15.09(s)	10.42(s)	24.30(s)
	^{35}Cl	CYE(WOD)	81.57(s)	88.49(s)	45.42(s)	66.17(s)	38.01(s)	39.80(s)	31.71(s)	53.71(s)
		CYE(WPD)	82.35(s)	75.30(s)	46.83(s)	60.75(s)	39.53(s)	45.94(s)	24.66(s)	37.79(s)
		CYE(WPC)	58.10(s)	64.36(s)	26.15(s)	43.39(s)	20.11(s)	21.42(s)	15.39(s)	33.40(s)
	^{40}Ar	CYE(WOD)	56.76(s)	60.50(s)	30.69(s)	103.8(s)	24.81(s)	24.98(s)	19.88(s)	42.50(s)
		CYE(WPD)	58.30(s)	60.44(s)	32.72(s)	113.1(s)	27.00(s)	31.44(s)	14.56(s)	33.17(s)
		CYE(WPC)	47.81(s)	50.43(s)	27.67(s)	91.86(s)	23.42(s)	26.92(s)	13.62(s)	29.07(s)
	^{39}K	CYE(WOD)	87.03(s)	97.00(s)	48.53(s)	71.85(s)	40.54(s)	42.30(s)	33.44(s)	58.43(s)
		CYE(WPD)	87.89(s)	81.80(s)	49.93(s)	80.38(s)	42.06(s)	49.18(s)	25.89(s)	47.30(s)
		CYE(WPC)	72.51(s)	80.66(s)	40.81(s)	64.40(s)	34.71(s)	39.88(s)	22.40(s)	40.56(s)
	^{40}Ca	CYE(WOD)	98.35(s)	112.16(s)	55.14(s)	81.37(s)	46.24(s)	48.41(s)	38.39(s)	65.97(s)
		CYE(WPD)	99.06(s)	94.72(s)	56.38(s)	90.45(s)	47.58(s)	55.34(s)	29.99(s)	53.79(s)
		CYE(WPC)	-	-	-	-	-	-	-	-
Decay mode			SF	SF	Alpha decay	SF	Alpha decay	SF	Alpha decay	SF

In this study, we used the CYE Model to estimate the previously well-known experimental half-lives of Superheavy elements Z=104-118. It is observed from the literature that there is no experimental study on the cluster decay of Superheavy nuclei till now, but observed alpha decay is available up to Z=118. Hence in this work, we have compared the calculated half lifetime values using our CYEM with the available theoretical [36,37] and experimental values [38] and are tabulated in Table 2. From this table, it is observed that the half lifetime values of our CYE model coincides well with the experimental half lifetime values.

Table 2. Analysis of the predicted alpha decay half-life using CYEM compared to available theoretical and experimental data.

Decay mode	Energy released Q (Exp)[33]	Log $T_{1/2}$ (s)				
		CYEM		Exp [39]	Royer [37]	UDL [38]
		WOD	WPD			
$^{256}_{104}Rf \rightarrow ^{252}No + ^{4}He$	8.93	0.82	0.34	0.32	0.16	-0.07344
$^{258}_{104}Rf \rightarrow ^{254}No + ^{4}He$	9.19	-0.03	-0.54	-0.98	-0.69	-0.59294
$^{260}_{104}Rf \rightarrow ^{256}No + ^{4}He$	8.90	0.85	0.31	0.02	0.16	0.695445
$^{260}_{106}Sg \rightarrow ^{256}Rf + ^{4}He$	9.90	-1.39	-1.88	-1.91	-2.00	-2.22087
$^{264}_{108}Hs \rightarrow ^{260}Sg + ^{4}He$	10.59	-2.58	-3.16	-2.97	-3.15	-3.39916

${}^{268}_{108}Hs \rightarrow {}^{264}Sg + {}^{4}He$	9.63	-0.67	0.03	0.15	-0.62	-0.91103
${}^{270}_{108}Hs \rightarrow {}^{266}Sg + {}^{4}He$	9.07	1.73	0.98	0.95	1.05	0.730885
${}^{270}_{110}Ds \rightarrow {}^{266}Hs + {}^{4}He$	11.12	-3.31	-3.90	-3.69	-3.84	-4.135
${}^{280}_{114}Fl \rightarrow {}^{276}Cn + {}^{4}He$	10.37	-0.19	-0.35	-0.46	-0.8	-1.20328
${}^{288}_{114}Fl \rightarrow {}^{284}Cn + {}^{4}He$	10.07	0.64	0.78	-0.12	0.003	-0.40664
${}^{294}_{116}Lv \rightarrow {}^{290}Fl + {}^{4}He$	11.01	-1.34	-1.53	-2.1	-1.85	-2.27973
${}^{296}_{116}Lv \rightarrow {}^{292}Fl + {}^{4}He$	10.78	-0.77	-1.01	-1.62	-1.29	-1.72474
${}^{294}_{118}Og \rightarrow {}^{290}Lv + {}^{4}He$	11.84	-2.73	-2.97	-2.94	-3.26	-3.71193

Fig. 1 shows the plot of comparison between the neutron number of the emitted nuclei (N_2) versus the calculated logarithmic α and CR decay half-lives of Superheavy nuclei ${}^{298,310}114$, ${}^{306,318}122$, ${}^{308,310}124$ and ${}^{310,322}126$ using CYEM along with and without the inclusion of deformation parameters. The comparison of the calculated alpha decay half-lives using CYEM with the available experimental values are shown in Fig. 2. From this Figure, it is clear that our calculated CYEM values are well coincides with the experimental values. A comparison of the predicted logarithmic half-lives for Superheavy nuclei using our CYE model was presented in Fig. 3. Figs. 3(a) and 3(b) illustrate that the α-decay and SF lifetime values varies with the predicted SHN. According to the Fig. 3(a), the logarithmic half-lives of ${}^{306}122$, ${}^{308}124$ and ${}^{310}126$ were smaller than those of other Superheavy nuclei. As shown in Figs. 3(c) and 3(d), the two panels compared the logarithmic half-lives of ${}^{20}Ne$ and ${}^{40}Ca$ with the predicted magic numbers of Superheavy nuclei. Figs. 3(c) and 3(d) demonstrate that Superheavy nuclei ${}^{306}122$ and ${}^{308}124$ have shorter lifetime values.

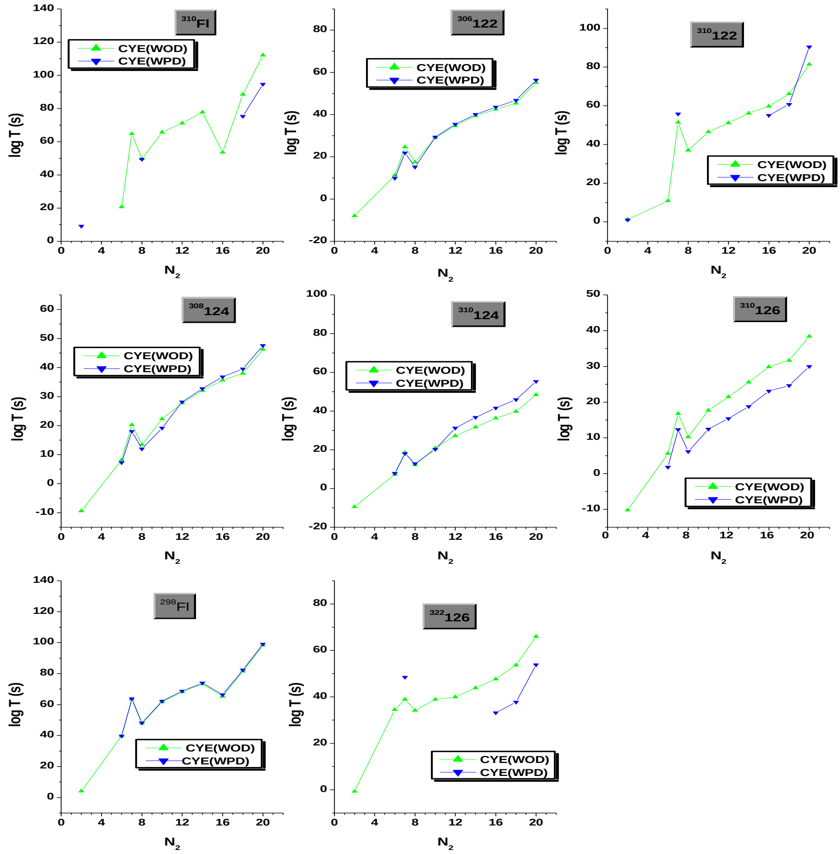

Fig. 1. The comparison plot between calculated alpha decay and CR decay of log T vs Neutron number of the emitted nuclei (N_2) using CYE model (WOD & WD) for predicted magic numbers of SHN.

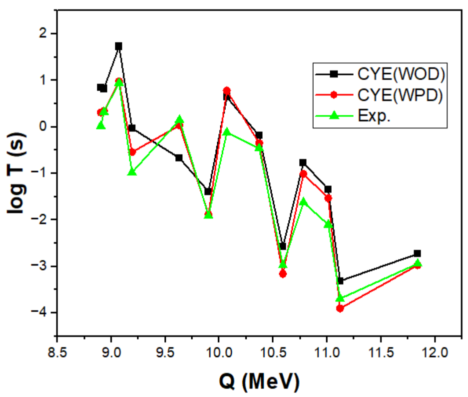

Fig. 2. The computed α-decay half lifetime values using CYEM are compared with the experimental values against the energy released during the emission (Q values in MeV).

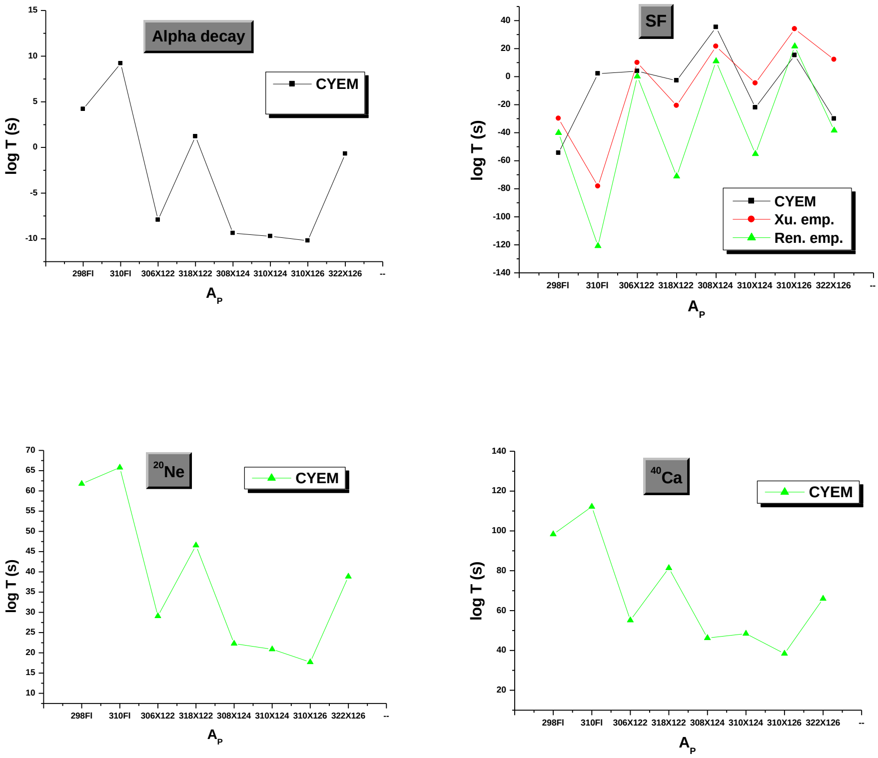

Fig. 3. The comparative plot of the calculated logarithmic α-decay and cluster decay half-lives of SHN using CYEM with the corresponding Spontaneous fission half-lives.

4. Conclusion

In the present work, we have examined the half-lives for different decay modes of Superheavy nuclei $^{298,310}114$, $^{306,318}122$, $^{308,310}124$ and $^{310,322}126$ using our Cubic plus Yukawa plus Exponential (CYE) model. It has been observed that the alpha decay is the dominant decay mode in the Superheavy nuclei $^{306}122$, $^{308}124$ and $^{310}126$ based on the comparison between alpha, cluster decay and SF half-lives. Thus, in this work we have predicted the dominant decay modes for Superheavy elements with magic number of neutrons and protons are studied using our Cubic plus Yukawa plus Exponential Model. Hence future experimental work can be focused on the synthesis of Superheavy nuclei with the magic numbers.

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