Systematic study of cluster radioactivity of superheavy nuclei

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The probable cluster radioactivity (CR) of $^{294}118$, $^{296}120$, and $^{298}122$ is studied by using the unified description (UD) formula, universal (UNIV) curve, Horoi formula, and universal decay law (UDL). The predictions by the former three models suggest that the probable emitted clusters are lighter nuclei, and the calculations within the UDL formula give a different prediction: that both the lighter clusters and heavier ones can be emitted from the parent nuclei. A further study on the competition between α decay and CR of $Z = 104$–124 isotopes is performed. The former three models predict that α decay is the dominant decay mode, but the UDL formula suggests that CR dominates over α decay for $Z \geqslant 118$ nuclei and the isotopes of $^{292-296,308-318}118$, $^{284-304,308-324}120$, and $^{316-322}122$ are the most likely candidates as the cluster emitters. Because the former three formulas are just preformation models, the lighter cluster emissions can be described. However, the UDL formula can predict the lighter and heavier CR owing to the inclusion of the preformation and fissionlike mechanisms. Finally, it is found that the shortest CR half-lives are always obtained when the daughter nuclei are around the double magic ^{208}Pb within the UDL formula, which indicates that shell effect has an important influence on CR.

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I. INTRODUCTION

Nowadays, the study of superheavy nuclei (SHN) has been an attractive subject in nuclear physics. So far, the elements with atomic number $Z \leqslant 118$ have been synthesized in hot fusion reactions of ^{48}Ca beams on actinide targets or with cold fusion using ^{208}Pb or ^{209}Bi as targets [1–10]. For SHN, α decay is one of the most important decay modes. The structure information of SHN, such as the half-life, radius, deformation, and shell effect, can be obtained by detecting α emitters. Thus many phenomenological and microscopic models have been proposed to describe α-decay process based on the Gamow's quantum tunneling effect [11–24]. In addition to α decay, cluster radioactivity (CR), which shares a similar physical mechanism with α radioactivity, is an important phenomenon for heavy nuclei. The CR was first predicted in 1980 by Sandulescu *et al.* [25], and then it was confirmed by Rose and Jones in 1984 for ^{14}C radioactivity from ^{223}Ra [26]. From then on, many kinds of clusters, such as ^{14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg, and ^{32,34}Si, have been experimentally observed in trans-lead parent nuclei of $Z = 87$–96 [27–31].

Recently, studies on CR of SHN have been paid attention by many researchers. Poenaru *et al.* predicted that CR is one of the important decay modes for SHN and its branching ratio is larger than that of α decay for $Z \geqslant 121$ nuclei by the analytical superasymmetric fission (ASAF) model [32–34]. Later, the calculations within the universal decay law (UDL) gave predictions similar to the ones of the ASAF [35]. As a matter of fact, besides the two models mentioned above, there exist many universal models or formulas to estimate the half-lives of α decay and CR, such as the unified description (UD) formula [36], the universal (UNIV) curve [37], and the Horoi formula [38]. This makes us wonder if the CR and larger branching ratio of CR relative to α decay really exist for heavier SHN if other universal models are employed. Thus, it is very necessary to use more models to work on the issue. In this article, we will investigate the competition between α decay and cluster decay of SHN by using the UD, UNIV, Horoi, and UDL formulas [39,40]. The paper is organized as follows. In Sec. II, the theoretical formulas are introduced. The numerical results and discussions are presented in Sec. III. A conclusion is given in the last section.

II. FORMULAS FOR α DECAY AND CR HALF-LIVES

The present calculations on α decay and CR half-lives are performed by using the UD, UNIV, Horoi, and UDL formulas. These formulas are written as follows:

$$\mathtt{log}_{10}T_{1/2}(\mathtt{UD}) = a\sqrt{\mu}Z_eZ_dQ^{-1/2} + b\sqrt{\mu}(Z_eZ_d)^{1/2} + c, \tag{1}$$

$$\begin{aligned}\mathtt{log}_{10}T_{1/2}(\mathtt{UNIV}) = {} & 0.22873(\mu Z_eZ_dR_b)^{1/2} \times [\arccos\sqrt{r} \\ & -\sqrt{r(1-r)}] + 0.598(A_e-1) \\ & +[\mathtt{log}_{10}(\mathtt{ln2}) - \mathtt{log}_{10}\nu] + h,\end{aligned} \tag{2}$$

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$$\mathtt{log}_{10}T_{1/2}(\mathtt{Horoi}) = (a_1\mu^x + b_1)[(Z_eZ_d)^y Q^{-1/2} - 7] + (a_2\mu^x + b_2), \tag{3}$$

$$\mathtt{log}_{10}T_{1/2}(\mathtt{UDL}) = a\sqrt{\mu}Z_eZ_dQ^{-1/2} + b\big[\mu Z_eZ_d\big(A_d^{1/3} + A_e^{1/3}\big)\big]^{1/2} + c, \tag{4}$$

where $T_{1/2}$ is the half-lives of α decay and CR, which is measured in seconds. Q in Eqs. (1)–(4) denotes the released energy in decay process and it is measured in MeV. $\mu = A_eA_d/(A_e{+}A_d)$ is the reduced mass. A_e and A_d represent the mass numbers of the emitted particle and daughter nucleus, respectively. Z_e and Z_d denote the charge numbers of the two fragments. In Eq. (2), $r = R_t/R_b$, R_t and R_b stand for the first and second turning points of the barrier, respectively. The two turning points are defined as $R_t = 1.2249\,(A_e^{1/3}{+}A_d^{1/3})$ and $R_b = 1.43998Z_eZ_d/Q$. The frequency of assaults ν is taken as $10^{22.01}$ s^{-1}. These parameters (a, b, c, h, a_1, b_1, a_2, b_2, x, y) are determined by fitting the experimental half-lives and Q values. The values of these parameters can be found in Refs. [34,36,38,39].

It is well known that the half-lives of α decay and CR are sensitive to the Q values, which are given by

$$Q = M_p - (M_d + M_e), \tag{5}$$

where M_p, M_d, and M_e represent the masses of the parent, daughter nucleus, and emitted particle, respectively. For most SHN, their masses have not been measured. But the unknown SHN masses can be estimated by the nuclear mass models. Equation (5) tells us that if one wants to obtain the accurate Q values, the selection of nuclear mass models is extremely important. A recent work of Wang *et al.* suggested that the WS4 mass model is the most accurate one to predict the Q_α values of SHN [41]. So, in this work, the WS4 mass table [42] is used. We know that the shell effects are important in determining the favorite emitted fragments and the half-lives, but Eqs. (1)–(4) are purely phenomenological models and the shell effects are included only through the Q values. So the approaches we use can be seen as approximate ones.

III. RESULTS AND DISCUSSION

First, we calculate the α decay and CR half-lives of ^{294}118, ^{296}120, and ^{298}122 by using the UD, UNIV, Horoi, and UDL formulas. The calculated half-lives are presented in Table I. The first column indicates the parent nuclei. The emitted clusters and the corresponding daughter nuclei are listed in columns 2 and 3, respectively. Note that each kind of emitted cluster refers to the most probable one. The Q values of α decay and CR extracted from the WS4 mass table are shown in column 4. The next four columns give the calculated α decay and CR half-lives by using the UD, UNIV, Horoi, and UDL formulas, respectively. As can be seen from Table I, for the ^{294}118 nucleus, the half-lives of CR become longer with the increase of the A_e values by using the UD, UNIV, and Horoi formulas. However, the present measurement upper limit of half-lives is 10^{30}s [43]. It is seen clearly from Table I that the half-lives of heavier cluster (heavier than ^{32}Si) emissions have exceeded the upper threshold, and these heavier CR cannot be observed in measurement. Hence, the probable clusters emitted from ^{294}118 are lighter nuclei (^{8}Be, ^{12}C, ^{16}O, ^{28}Mg, ^{32}Si). But within the UDL formula, the half-lives of all the cluster emissions shown in Table I are less than 10^{30}s. So these clusters might be detected in experiments, which include both the lighter nuclei (^{8}Be, ^{12}C, ^{16}O, ^{28}Mg, ^{32}Si) and heavier ones (^{68}Ni, ^{76}Zn, ^{79}Ga, ^{80}Ge, ^{83}As, ^{84}Se, ^{85}Br, ^{85}Kr, ^{89}Rb, ^{89}Sr, and so forth). In addition, an interesting case that the CR half-life is shorter than the corresponding α-decay half-life is found in Table I, such as ^{85}Kr emission. It means that the heavier CR dominates over α decay for ^{294}118. Finally, the shortest half-life is found when the daughter nucleus is the double-magic nucleus ^{208}Pb for the heavier CR half-lives extracted from each formula. This fact reveals that the cluster decay is strongly related to the shell effect. As for the CR of ^{296}120 and ^{298}122, it is seen from Table I that the results are similar to the ones of ^{294}118. From the above analysis, we know that the CR half-lives within the UDL formula show significant difference from those within the UD, UNIV, and Horoi formulas. So it is not difficult to conclude that the CR half-lives are dependent on models. Meanwhile, it is obvious that within the UDL formula CR has a chance to compete with α decay for the three nuclei. In order to see whether the obvious CR exists for other SHN, it is necessary to extend the study to more SHN. In the next paragraphs, we will perform an extensive study on the competition between α decay and CR of SHN with $Z = 104$–124 by using the four formulas.

To gain a better insight into the competition between α decay and CR, ones usually define the branching ratio b_c of CR relative to the corresponding α decay as

$$\mathtt{log}_{10}b_c = \mathtt{log}_{10}(\lambda_c/\lambda_\alpha) = \mathtt{log}_{10}(T_\alpha/T_c), \tag{6}$$

where λ_c and λ_α denote the decay constants of CR and α decay, respectively. According to Eq. (6), we know that if $\log_{10}b_c > 0$, it represents that the CR is the dominant decay mode against α decay.

Decimal logarithm of b_c for the most probable emitted clusters versus the neutron number N of parent nuclei by the UD, UNIV, Horoi, and UDL formulas are presented in Fig. 1. From Fig. 1, we find that the $\mathtt{log}_{10}b_c$ values become longer with the increase of Z, which indicates that the CR becomes more evident. In addition, $\log_{10}b_c \ll 0$ is observed in Figs. 1(a)–1(c), which means that the α-decay half-lives are much shorter than the corresponding CR ones by using the UD, UNIV, and Horoi formulas. So the α decay is the dominant decay mode and it is impossible to observe the CR phenomenon in the superheavy region. However, in Fig. 1(d), $\log_{10}b_c > 0$ is observed for isotopes with $Z \geqslant 118$. This suggests that the CR is the main decay mode and it is very possible to observe CR in this region within the UDL formula. Finally, the kink of $\mathtt{log}_{10}b_c$ occurs at $N = 186$ in Figs. 1(a)–1(d), which may be an indication that the region about $N = 184$ is associated with a magic number. In fact, the magic number at $N = 184$ originates from the WS4 Q values. If we calculate the half-lives by inputting other kinds of Q values, the neutron closure after 126 may be changed because the magic numbers are dependent on different models [44–51]. However, many theories including both phenomenological models and microscopic models suggest the strong shell effect at $N = 184$

TABLE I. The probable CR half-lives of $^{294}118$, $^{296}120$, and $^{298}122$ within the UD, UNIV, Horoi, and UDL formulas.

Parent	Emitted	Daughter	Q	$T_{1/2}$(s)			
nuclei	clusters	nuclei	(MeV)	UD	UNIV	Horoi	UDL
$^{294}118$	^{4}He	^{290}Lv	12.198	4.22×10^{-4}	3.07×10^{-5}	1.60×10^{-4}	2.17×10^{-4}
	^{8}Be	^{286}Fl	23.191	1.90×10^{16}	9.19×10^{12}	7.75×10^{14}	1.21×10^{16}
	^{12}C	^{282}Cn	40.527	5.10×10^{21}	6.79×10^{16}	4.02×10^{19}	1.14×10^{21}
	^{16}O	^{278}Ds	57.459	9.67×10^{27}	3.08×10^{21}	1.57×10^{25}	2.48×10^{26}
	^{28}Mg	^{266}Sg	100.134	4.11×10^{30}	1.27×10^{23}	5.18×10^{29}	8.16×10^{24}
	^{32}Si	^{262}Rf	119.316	8.53×10^{31}	1.10×10^{24}	7.58×10^{31}	3.13×10^{24}
	^{68}Ni	^{226}Th	238.478	5.65×10^{38}	1.43×10^{35}	3.50×10^{47}	4.42×10^{14}
	^{76}Zn	^{218}Ra	253.586	6.80×10^{38}	9.13×10^{37}	2.57×10^{49}	3.66×10^{11}
	^{79}Ga	^{215}Fr	260.104	1.70×10^{39}	1.72×10^{39}	2.40×10^{50}	5.75×10^{10}
	^{80}Ge	^{214}Rn	271.603	1.52×10^{34}	8.24×10^{36}	6.54×10^{47}	1.61×10^{5}
	^{83}As	^{211}At	278.428	7.48×10^{33}	8.79×10^{37}	2.21×10^{48}	5.69×10^{3}
	^{84}Se	^{210}Po	289.282	1.98×10^{29}	1.37×10^{36}	1.24×10^{46}	4.94×10^{-2}
	^{85}Br	^{209}Bi	293.791	2.10×10^{30}	8.73×10^{36}	1.42×10^{47}	1.51×10^{-1}
	^{86}Kr	^{208}Pb	302.052	6.64×10^{27}	1.59×10^{36}	1.34×10^{46}	1.55×10^{-4}
	^{89}Rb	^{205}Tl	302.831	1.23×10^{32}	2.37×10^{39}	1.84×10^{49}	2.22×10^{-1}
	^{90}Sr	^{204}Hg	308.309	4.36×10^{31}	3.49×10^{39}	2.52×10^{49}	2.59×10^{-2}
	^{96}Y	^{198}Au	305.227	3.53×10^{39}	7.76×10^{45}	7.12×10^{54}	3.00×10^{4}
	^{96}Zr	^{198}Pt	313.309	1.21×10^{36}	1.55×10^{44}	1.30×10^{53}	7.07×10^{0}
	^{99}Nb	^{195}Ir	312.012	2.97×10^{41}	1.05×10^{48}	5.16×10^{56}	1.85×10^{5}
	^{102}Mo	^{192}Os	317.721	1.59×10^{40}	6.25×10^{48}	3.03×10^{56}	1.42×10^{3}
$^{296}120$	^{4}He	^{292}Og	13.343	7.73×10^{-6}	6.02×10^{-7}	3.90×10^{-6}	4.04×10^{-6}
	^{8}Be	^{288}Lv	25.491	3.82×10^{12}	2.17×10^{9}	2.17×10^{11}	2.46×10^{12}
	^{12}C	^{284}Fl	44.148	1.91×10^{17}	4.93×10^{12}	4.15×10^{15}	4.12×10^{16}
	^{16}O	^{280}Cn	61.512	8.61×10^{23}	5.95×10^{17}	5.72×10^{21}	1.95×10^{22}
	^{32}Si	^{264}Sg	124.595	1.01×10^{29}	4.10×10^{21}	6.48×10^{29}	2.28×10^{21}
	^{48}Ca	^{248}Fm	183.712	1.09×10^{31}	1.80×10^{25}	3.08×10^{36}	8.75×10^{15}
	^{68}Ni	^{228}U	246.315	4.75×10^{37}	5.91×10^{33}	6.70×10^{46}	1.96×10^{12}
	^{74}Zn	^{222}Th	260.014	1.47×10^{39}	3.093×10^{36}	1.88×10^{49}	1.20×10^{11}
	^{77}Ga	^{219}Ac	265.898	2.84×10^{40}	1.57×10^{38}	6.18×10^{50}	1.19×10^{11}
	^{80}Ge	^{216}Ra	277.568	1.68×10^{36}	1.04×10^{37}	7.71×10^{48}	2.95×10^{5}
	^{83}As	^{213}Fr	284.188	2.44×10^{36}	1.69×10^{38}	4.75×10^{49}	2.45×10^{4}
	^{84}Se	^{212}Rn	295.765	3.95×10^{31}	1.63×10^{36}	1.62×10^{47}	7.82×10^{-2}
	^{85}Br	^{211}At	301.050	1.39×10^{32}	6.08×10^{36}	9.58×10^{47}	7.37×10^{-2}
	^{86}Kr	^{210}Po	310.323	1.38×10^{29}	6.00×10^{35}	4.07×10^{46}	1.67×10^{-5}
	^{87}Rb	^{209}Bi	313.544	1.11×10^{31}	9.19×10^{36}	1.46×10^{48}	4.08×10^{-4}
	^{90}Sr	^{206}Pb	321.374	1.81×10^{29}	3.21×10^{37}	5.38×10^{47}	4.48×10^{-7}
	^{93}Y	^{203}Tl	321.251	5.21×10^{33}	1.72×10^{41}	7.03×10^{50}	1.73×10^{-2}
	^{96}Zr	^{200}Hg	326.668	4.71×10^{33}	1.18×10^{42}	3.12×10^{51}	1.11×10^{-4}
	^{103}Nb	^{193}Au	319.303	8.29×10^{44}	3.38×10^{50}	8.81×10^{58}	4.09×10^{5}
	^{100}Mo	^{196}Pt	330.182	3.29×10^{38}	9.08×10^{45}	1.48×10^{55}	3.56×10^{-1}
$^{298}122$	^{4}He	$^{294}120$	14.703	9.88×10^{-8}	9.11×10^{-9}	7.36×10^{-8}	5.26×10^{-8}
	^{8}Be	^{290}Og	27.853	1.78×10^{9}	3.19×10^{6}	1.47×10^{8}	1.78×10^{9}
	^{12}C	^{286}Lv	47.820	1.96×10^{13}	2.68×10^{9}	1.18×10^{12}	4.03×10^{12}
	^{16}O	^{282}Fl	65.924	6.12×10^{19}	2.84×10^{14}	1.95×10^{18}	1.23×10^{18}
	^{30}Si	^{268}Hs	129.371	2.72×10^{25}	5.62×10^{18}	7.95×10^{26}	2.25×10^{18}
	^{48}Ca	^{250}No	189.428	3.57×10^{29}	2.49×10^{24}	5.36×10^{35}	1.15×10^{14}
	^{66}Ni	^{232}Pu	254.864	1.25×10^{34}	2.57×10^{31}	1.22×10^{45}	3.06×10^{9}
	^{72}Zn	^{226}U	268.023	3.16×10^{36}	4.38×10^{34}	1.66×10^{48}	1.46×10^{9}
	^{75}Ga	^{223}Pa	273.130	5.23×10^{38}	6.67×10^{36}	2.18×10^{50}	1.13×10^{10}

TABLE I. *(Continued.)*

Parent	Emitted	Daughter	Q	$T_{1/2}$(s)			
nuclei	clusters	nuclei	(MeV)	UD	UNIV	Horoi	UDL
	^{80}Ge	^{218}Th	284.103	5.45×10^{35}	1.70×10^{37}	4.24×10^{49}	1.56×10^{5}
	^{81}As	^{217}Ac	291.006	2.32×10^{35}	2.12×10^{37}	7.87×10^{49}	1.72×10^{4}
	^{84}Se	^{214}Ra	302.865	6.46×10^{30}	2.62×10^{36}	9.69×10^{47}	3.44×10^{-2}
	^{85}Br	^{213}Fr	308.858	8.23×10^{30}	6.27×10^{36}	3.33×10^{48}	1.19×10^{-2}
	^{86}Kr	^{212}Rn	318.853	2.48×10^{27}	4.58×10^{35}	9.25×10^{46}	1.10×10^{-6}
	^{87}Rb	^{211}At	322.851	6.96×10^{28}	4.20×10^{36}	1.77×10^{48}	8.50×10^{-6}
	^{90}Sr	^{208}Po	330.997	8.17×10^{26}	1.55×10^{37}	6.80×10^{47}	8.19×10^{-9}
	^{89}Y	^{209}Bi	332.454	6.10×10^{29}	5.77×10^{37}	4.31×10^{49}	6.49×10^{-6}
	^{94}Zr	^{204}Pb	340.201	1.29×10^{28}	2.74×10^{39}	3.68×10^{49}	3.47×10^{-9}
	^{97}Nb	^{201}Tl	340.292	2.35×10^{32}	3.20×10^{42}	3.51×10^{52}	5.56×10^{-6}
	^{98}Mo	^{200}Hg	345.208	1.12×10^{32}	6.11×10^{42}	5.31×10^{52}	9.31×10^{-7}

[46–51], which is expected to be tested experimentally in the future.

Next we will analyze the factors contributing to the different calculations by Eqs. (1)–(3) and (4). Equations (1)–(3) can be seen as the preformation models because the α-particle and cluster preformation probabilities are included. Owing to the same mechanism, the calculations by the three models are similar. As we all know that as the emitted cluster is lighter, the preformation probability of cluster inside parent nucleus is larger. Thus, the lighter CR can be predicted by the three models. But for the heavier CR of SHN, it is more similar to the cold spontaneous fission, so the preformation models are not suitable for describing the radioactivity of very heavy cluster. However, the UDL formula can be treated as both the preformation model and the fission-like model. As a result, the lighter and heavier CR of SHN can be predicted. Therefore, we may draw a conclusion that the UD, UNIV, and Horoi formulas are not suitable for predicting the half-lives of very heavy CR of SHN and the UDL formula seems more universal and reasonable. In the next paragraph, we will attempt to make predictions for the possible CR of $Z \geqslant 118$ within the UDL formula.

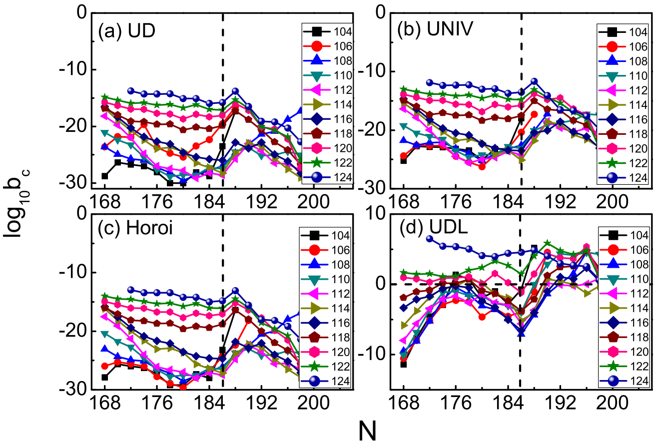

FIG. 1. Decimal logarithm of b_c vs the neutron number N of parent nuclei within the UD, UNIV, Horoi, and UDL formulas.

The half-lives of α decay and CR of SHN with $Z = 118, 120$, and 122 isotopes are given in Table II. The first column are the parent nuclei. The Q values and half-lives of α decay are given in columns 2 and 3, respectively. Columns 4 and 5 represent the most favored emitted clusters and the corresponding daughter nuclei, respectively. The Q values and half-lives of cluster decay are listed in the last two columns. It is seen from Table II that all the daughter nuclei are closed to ^{208}Pb for the most probable CR. In addition, the most probable cluster emitters are the isotopes of $^{292\text{–}296,308\text{–}318}$118, $^{284\text{–}304,308\text{–}324}$120, and $^{290\text{–}322}$122, which have the larger branching ratios and relatively shorter half-lives. Hence, these nuclides are the most likely candidates as the cluster emitters in future measurement. However, it should be pointed out that the CR half-lives of $^{290\text{–}314}$122 are much less than 1 μs, so it is very difficult or even impossible to observe CR phenomenon with the current facilities. We hope our predictions on α decay and CR may be useful for further experiments.

IV. CONCLUSIONS

In this article, the probable CR of ^{294}118, ^{296}120, and ^{298}122 has been studied by using the UD, UNIV, Horoi, and UDL formulas. The calculations within the UD, UNIV, and Horoi formulas suggest that the favored emitted clusters are lighter nuclei. But the UDL formula gives a different prediction: that the most probable emitted clusters are heavier ones. Later, a further study on the branching ratios of CR relative to α decay of Z =104–124 has been performed. The calculated results obtained by the UD, UNIV, and Horoi formulas show that the dominant decay mode of SHN is α decay. However, the UDL formula predicts that CR dominates over α decay for the $Z \geqslant$ 118 nuclei. Because the UD, UNIV, and Horoi formulas are seen as the preformation models, the lighter cluster emissions can be described by these formulas. But for the UDL formula, the preformation and fission-like mechanisms are all included, so the lighter and heavier CR of SHN can be well predicted. Thus, we can conclude that the UD, UNIV, and Horoi for-

TABLE II. The half-lives of α decay and the most probable CR of $Z = 118$, 120, and 122 within the UDL formula.

Parent nuclei	Q_α (MeV)	T_α(s)	Emitted clusters	Daughter nuclei	Q_c (MeV)	T_c (s)
$^{286}118$	12.915	9.67×10^{-6}	^{86}Kr	^{200}Pb	303.281	7.68×10^{-4}
$^{288}118$	12.616	3.57×10^{-5}	^{86}Kr	^{202}Pb	303.080	4.14×10^{-4}
$^{290}118$	12.601	3.59×10^{-5}	^{86}Kr	^{204}Pb	302.835	2.44×10^{-4}
$^{292}118$	12.240	1.88×10^{-4}	^{86}Kr	^{206}Pb	302.669	1.24×10^{-4}
$^{294}118$	12.198	2.17×10^{-4}	^{86}Kr	^{208}Pb	302.052	1.55×10^{-4}
$^{296}118$	11.752	1.94×10^{-3}	^{88}Kr	^{208}Pb	300.843	3.80×10^{-4}
$^{298}118$	12.182	2.06×10^{-4}	^{90}Kr	^{208}Pb	299.372	1.67×10^{-3}
$^{300}118$	11.956	5.98×10^{-4}	^{94}Sr	^{206}Hg	306.681	1.24×10^{-2}
$^{302}118$	12.041	3.65×10^{-4}	^{96}Sr	^{206}Hg	305.025	8.73×10^{-2}
$^{304}118$	13.122	2.12×10^{-6}	^{98}Sr	^{206}Hg	305.211	1.32×10^{-2}
$^{306}118$	12.480	3.76×10^{-5}	^{102}Zr	^{204}Pt	313.080	5.03×10^{-3}
$^{308}118$	11.204	2.52×10^{-2}	^{104}Zr	^{204}Pt	312.958	1.42×10^{-3}
$^{310}118$	10.433	2.23×10^{0}	^{106}Zr	^{204}Pt	311.464	7.70×10^{-3}
$^{312}118$	9.761	1.70×10^{2}	^{106}Zr	^{206}Pt	309.085	4.56×10^{-1}
$^{314}118$	8.383	6.42×10^{6}	^{111}Nb	^{203}Ir	309.483	1.10×10^{2}
$^{316}118$	8.619	8.23×10^{5}	^{111}Nb	^{205}Ir	307.317	4.82×10^{3}
$^{318}118$	8.413	4.40×10^{6}	^{113}Nb	^{205}Ir	305.209	1.44×10^{5}
$^{320}118$	9.164	9.73×10^{3}	^{113}Nb	^{207}Ir	304.172	5.38×10^{5}
$^{284}120$	13.990	3.95×10^{-7}	^{88}Sr	^{196}Pb	326.337	3.69×10^{-8}
$^{286}120$	14.025	3.20×10^{-7}	^{88}Sr	^{198}Pb	325.580	5.24×10^{-8}
$^{288}120$	13.725	1.03×10^{-6}	^{88}Sr	^{200}Pb	324.624	1.08×10^{-7}
$^{290}120$	13.700	1.07×10^{-6}	^{88}Sr	^{202}Pb	323.781	1.85×10^{-7}
$^{292}120$	13.467	2.69×10^{-6}	^{90}Sr	^{202}Pb	321.909	1.32×10^{-6}
$^{294}120$	13.242	6.73×10^{-6}	^{88}Sr	^{206}Pb	321.873	8.67×10^{-7}
$^{296}120$	13.343	4.04×10^{-6}	^{90}Sr	^{206}Pb	321.374	4.48×10^{-7}
$^{298}120$	13.007	1.69×10^{-5}	^{92}Sr	^{206}Pb	319.945	1.47×10^{-6}
$^{300}120$	13.318	3.93×10^{-6}	^{94}Sr	^{206}Pb	318.694	3.55×10^{-6}
$^{302}120$	12.890	2.53×10^{-5}	^{94}Sr	^{208}Pb	318.940	7.51×10^{-7}
$^{304}120$	12.763	4.27×10^{-5}	^{96}Sr	^{208}Pb	316.437	2.41×10^{-5}
$^{306}120$	13.787	4.36×10^{-7}	^{100}Zr	^{206}Hg	324.888	6.24×10^{-6}
$^{308}120$	12.966	1.47×10^{-5}	^{102}Zr	^{206}Hg	325.346	4.95×10^{-7}
$^{310}120$	11.499	2.10×10^{-2}	^{104}Zr	^{206}Hg	324.275	9.12×10^{-7}
$^{312}120$	11.216	9.50×10^{-2}	^{106}Zr	^{206}Hg	322.147	1.60×10^{-5}
$^{314}120$	10.759	1.30×10^{0}	^{106}Zr	^{208}Hg	320.244	2.98×10^{-4}
$^{316}120$	9.192	5.13×10^{4}	^{106}Zr	^{210}Hg	316.643	2.29×10^{-1}
$^{318}120$	9.931	2.32×10^{2}	^{111}Nb	^{207}Au	317.991	9.25×10^{0}
$^{320}120$	9.678	1.26×10^{3}	^{111}Nb	^{209}Au	315.951	2.87×10^{2}
$^{322}120$	9.368	1.13×10^{4}	^{111}Nb	^{211}Au	313.952	8.63×10^{3}
$^{324}120$	7.993	1.05×10^{9}	^{113}Nb	^{211}Au	311.675	3.69×10^{5}
$^{326}120$	9.290	1.79×10^{4}	^{113}Nb	^{213}Au	311.483	1.96×10^{5}
$^{328}120$	8.518	8.34×10^{6}	^{115}Nb	^{213}Au	309.060	1.34×10^{7}
$^{290}122$	15.108	1.50×10^{-8}	^{92}Zr	^{198}Pb	344.186	3.06×10^{-10}
$^{292}122$	15.015	1.98×10^{-8}	^{92}Zr	^{200}Pb	343.141	6.94×10^{-10}
$^{294}122$	14.666	6.94×10^{-8}	^{92}Zr	^{202}Pb	331.949	2.11×10^{-9}
$^{296}122$	14.695	5.82×10^{-8}	^{88}Sr	^{208}Po	332.257	4.05×10^{-9}
$^{298}122$	14.703	5.26×10^{-8}	^{94}Zr	^{204}Pb	340.201	3.47×10^{-9}
$^{300}122$	14.222	3.28×10^{-7}	^{94}Zr	^{206}Pb	339.656	3.25×10^{-9}
$^{302}122$	14.237	2.89×10^{-7}	^{96}Zr	^{206}Pb	339.306	1.17×10^{-9}
$^{304}122$	13.738	2.14×10^{-6}	^{96}Zr	^{208}Pb	338.812	1.01×10^{-9}

TABLE II. *(Continued.)*

Parent nuclei	Q_α (MeV)	T_α(s)	Emitted clusters	Daughter nuclei	Q_c (MeV)	T_c (s)
^{306}122	13.803	1.52×10^{-6}	^{98}Zr	^{208}Pb	337.340	3.30×10^{-9}
^{308}122	14.940	1.53×10^{-8}	^{100}Zr	^{208}Pb	337.453	4.93×10^{-10}
^{310}122	13.356	5.94×10^{-6}	^{102}Zr	^{208}Pb	337.546	5.60×10^{-10}
^{312}122	12.162	2.56×10^{-3}	^{104}Zr	^{208}Pb	334.816	3.46×10^{-9}
^{314}122	12.117	3.04×10^{-3}	^{104}Zr	^{210}Pb	332.947	5.09×10^{-8}
^{316}122	11.659	3.22×10^{-2}	^{104}Zr	^{212}Pb	330.694	1.74×10^{-6}
^{318}122	10.638	1.16×10^{1}	^{106}Zr	^{212}Pb	327.722	1.77×10^{-4}
^{320}122	11.656	2.88×10^{-2}	^{106}Zr	^{214}Pb	325.713	4.23×10^{-3}
^{322}122	11.239	2.79×10^{-1}	^{106}Zr	^{216}Pb	323.542	1.51×10^{-1}
^{324}122	12.179	1.61×10^{-3}	^{111}Nb	^{213}Tl	326.378	3.25×10^{-1}

mulas are not suitable for describing the heavier CR of SHN and the UDL formula seems more universal and reasonable. Based on the conclusion, we predict the most probable CR of $Z = 118$, 120, and 122 isotopes by using the UDL formula. The results show that the isotopes of $^{292\text{–}296,308\text{–}318}$118, $^{284\text{–}304,308\text{–}324}$120, and $^{316\text{–}322}$122 are the most likely candidates as the cluster emitters. Finally, the parent nuclei probably emit clusters when the daughter nuclei are close to ^{208}Pb, which implies that shell effect plays an important role on CR.

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