https://doi.org/10.15407/ujpe69.10.712

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STUDY OF CLUSTER DECAYS INCLUDING THOSE LEADING TO DOUBLY MAGIC NUCLEUS ^{298}114 AND BRANCHING RATIOS RELATIVE TO ALPHA DECAY

The study of superheavy nuclei (SHN) and their decay properties is one of the rapidly growing fields in nuclear physics. Using the CYE model, we have already studied the decay properties of the alpha decay, cluster decay, and spontaneous fission of the heavy and superheavy nuclei. In the present work, we will examine the effects by incorporating hexacontatetrapole (β_6) parameter in the parent nucleus along with the quadrupole (β_2), and hexadecapole (β_4) deformations of the decaying parent nucleus emitting clusters $^{8}_{4}Be$ and $^{12}_{6}C$. These deformations lower the half-life values, because they reduce the height and width of the potential barrier. Additionally, the creation of the doubly magic daughter $^{298}114$ from different decaying nuclei is computed. The calculated half-lives are compared with other models and are found to be in a good agreement. The branching ratios relative to the alpha-decay have also been calculated.

Keywords: decay half-life, Q-value, deformation , doubly magic nuclei, branching ratio.

1. Introduction

The spontaneous emission of fragments heavier than alpha particle, but lighter than fission fragments termed as cluster radioactivity or heavy particle decay. In 1980, the cluster decay was first predicted, on the basis of quantum mechanical fragmentation theory. The emitted clusters are heavier than the alpha particles, but lighter than the fission fragments; this is meant to be the process intermediate among the alpha decay and spontaneous fission (SF). In 1984, Rose and Jones have detected ^{14}C emission from ^{223}Ra with branching ratio corresponding to alpha particles as $8.5\pm2.5\times10^{-10}$, with a solid-state counter telescope. Since then, the emissions of ^{14}C, ^{20}O, ^{23}F, ^{22,24,26}Ne, ^{28,30}Mg and ^{32,34}Si have been measured [1, 2, 3] in heavy nuclei mass region with $Z = 87$–96. Cluster radioactivity is considered as a rare and cold process. It is considered as a cold process, because neutrons are not emitted during the process, and it is considered as rare, because the cluster emissions are masked by several alpha decay events. Distinguishing between these decay modes and the numerous pile-up of alpha particle pulses is the main challenge in cluster decay detection. The role of deformation effect on

Citation: Bai G.M. Carmel Vigila, Ajithra V.S. Study of cluster decays including those leading to doubly magic nucleus ^{298}114 and branching ratios relative to alpha decay. *Ukr. J. Phys.* **69**, No. 10, 712 (2024). https://doi.org/10.15407/ujpe69.10.712.

half-lives in the cluster decay has been calculated by many authors [4, 5, 6, 7], using different theoretical models. In heavy nuclei, the experiments have been able to detect cluster emissions occurring with observed branching ratios as low as 10^{-9}–10^{-17} [8]. We have already studied the decay properties of α – decay in SHE [9, 10]. Again, we have studied the decay properties of α decay in SHE for even nuclei ($Z = 128$, 130, 132, 134, 136, 138, 140, 142, and 144) and odd nuclei $Z = 127$–129 [11, 12, 13, 14, 15, 16]. In this present work, we will calculate the decay properties of the cluster decay of SHE in the region $Z = 130$–138. In the super heavy region, $Z = 114$ and $N = 184$ nuclei are expected to be doubly magic. In this paper, the formation of the doubly magic daughter $^{298}114$ from different decaying parents with the emission of clusters with the most favorable decay chain rs considered. The branching ratio is the ratio of the fraction of nuclei that will decay via cluster emission concerning nuclei decaying via alp,ha emissions, and it can be obtained using the relation, $\mathrm{BR} = \frac{T^{\alpha}_{1/2}}{T^{\mathrm{cluster}}_{1/2}}$. We have calculated the branching ratio of the cluster decay relative to the corresponding alpha-decay as,

$$\mathrm{Log}_{10}\mathrm{BR} = \mathrm{Log}_{10}\left(\frac{\lambda_{\mathrm{c}}}{\lambda_{\alpha}}\right) = \mathrm{Log}_{10}\left(\frac{T_{\alpha}}{T_{\mathrm{c}}}\right),$$

where λ_{c} and λ_{α} are the decay constants for cluster and alpha emissions, T_{α} and T_{c} are the half-lives for alpha and cluster emissions, respectively. Ratio values ($\log_{10}\mathrm{BR}$) have been calculated as $\log_{10}[T_{\alpha}(s)] - \log_{10}[T_{\mathrm{c}}(s)]$. We have done our calculations by considering Coulomb and Yukawa plus exponential potentials as interacting barrier for separated fragments and cubic potential for the overlap region described in Section 2. The results and discussion are given in Section 3. Finally, the conclusions are given in Section 4.

2. Cubic Plus Yukawa Plus Exponential (CYE) Model

In this work, we use a realistic model [17], known as the CYE model, to examine the decay properties. In this model, a cubic potential in the pre-scission zone is connected to a Coulomb plus Yukawa plus Exponential potential in the post-scission region. Without going against the principle of energy conservation, the zero-point vibration energy is expressly incorporated here. The proton pairs are already present in the nucleus at a specific distance from the nucleus, and the proton particle only encounters pure Coulomb potential. This potential as a function of r which is the center of mass distance of the two fragments for the post scission region is given by

$$V(r) = \frac{Z_1 Z_2 e^2}{r} + V_n(r) - Q, \quad r \geq r_t. \tag{1}$$

3. Potential for the Post-Scission Region

The parent and daughter nuclei are regarded as spheroid in this work. If the ejected nucleus is spherical, and the daughter nucleus only exhibits a single deformation, such as a quadruple deformation, and if the reaction's Q value is assumed to be the origin, then the potential for the post-scission is given by,

$$V(r) = V_c(r) - V_{df}(r) - Q, \quad r \geq r_t. \tag{2}$$

Here, $V_c(r)$ is the Coulomb potential between a spheroidal daughter and spherical emitted fragment, $V_n(r)$ is the nuclear interaction energy due to finite range effects, $V_{df}(r)$ is a change in the nuclear interaction energy due to quadruple deformation (β_2) of the daughter nucleus.

For a prolate spheroid daughter nucleus with longer axis along the fission direction,

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

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

$$V_c(r) = \frac{3}{2}\frac{z_1 z_2 e^2 \gamma}{r}[\gamma(1+\gamma^2)\arctan\gamma^{-1} - \gamma^2], \tag{4}$$

where z_1 and z_2 are the atomic number of the daughter and emitted clusters, respectively

$$\gamma = \frac{r}{(a_2^2 - b_2^2)^{1/2}}.$$

Here, a_2 and b_2 are the semi-major and minor axes of the spheroidal daughter nucleus, respectively.

If the nuclei have spheroid shape, the radius vector $R(\theta)$ making an angle θ with the axis of symmetry locating sharp surface of a deformed nuclei is given by

$$R(\theta) = R_0\left[1 + \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\beta_{nm}Y_{nm}(\theta)\right]. \tag{5}$$

Here, R_0 is the radius of the equivalent spherical nucleus.

A Change in the nuclear interaction energy due to the quadruple deformation β_2 of the daughter nucleus is given by

$$V_d = \frac{4R_2^3 C_s A_2 \beta_2}{a r_0^2} \left(\frac{5}{4\pi}\right)^{1/2}.$$

4. Potential for the Pre-Scission Region

A third order polynomial in r provides an approximation of the potential barrier's shape in the overlapped region between the ground state and the contact point

$$V(r) = -E(v) + [V(r_t) + E_v]\left\{s_1 \left[\frac{r - r_i}{r_t - r_i}\right]^2 - \right.$$
$$\left. - s_2 \left[\frac{r - r_i}{r_t - r_i}\right]^3\right\}, \quad r_i \le r \le r_t, \tag{6}$$

where r_i is the distance between the centers of mass of two portions of the daughter and the emitted nuclei in the spheroidal parent nucleus, and $r_t = a_2 + R_1$. Here, a_2 is the semi-major or minor axis of the spheroidal daughter nucleus depending on the shape.

If we consider spheroid deformation β_2, then

$$R(\theta) = R_0 \left[1 + \beta_2 \left(\frac{5}{4\pi}\right)^{1/2} \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)\right] \tag{7}$$

and if the Nilsson's hexadecapole deformation β_4 is also included in the deformation; then Eq. (6) becomes

$$R(\theta) = R_0 \left[1 + \beta_2 \left(\frac{5}{4\pi}\right)^{1/2} \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + \right.$$
$$+ \beta_4 \left(\frac{9}{4\pi}\right)^{1/2} \frac{1}{8}(35\cos^4\theta - 30\cos^2\theta + 3) + \beta_6 \sqrt{\frac{13}{4\pi}} \times$$
$$\left. \times \left(\frac{1}{16} 9231\cos^6\theta - 315\cos^4\theta + 105\cos^2\theta - 5\right)\right]. \tag{8}$$

For calculating the zero point vibration energy E_v,

$$Ev = \frac{\pi\hbar}{2}\left[\frac{\left(\frac{2Q}{\mu}\right)^{1/2}}{(C_1 + C_2)}\right],$$

C_1 and C_2 are the central radii of the fragments given by

$$C_i = 1.18A^{1/3} - 0.48 \quad (i = 1, 2)$$

and reduced mass,

$$\mu = \frac{m_1 m_2}{m_1 + m_2},$$

where $V_n(r)$ is the nuclear interaction energy and can be written in the form

$$V_n(r) = -D\left[F + \frac{r - r_t}{a}\right]\frac{r_t}{r}\exp\left[\frac{r_t - r}{a}\right].$$

Using the relation, the system's half-life is estimated as.

$$T = \frac{1.433 \times 10^{-21}}{E_v}[1 + \exp(K)],$$

where

$$K = \frac{2}{\hbar}\int_{r_a}^{r_t} [2B_r(r)V(r)]^{1/2}\, dr + \frac{2}{\hbar}\int_{r_t}^{r_b} [2B_r(r)V(r)]^{1/2}\, dr.$$

Here, r_a and r_b are the two appropriate zeros of the integrand.

5. Results and Discussion

In this work, the cluster radioactivity from super heavy nuclei $Z = 130$–136 is investigated by using CYE model. Furthermore, the formation of the doubly magic daughter $^{298}114$ from different decaying parents was considered, and the half-lives are compared with other theoretical models and with the universal decay law (UDL) by Qi *et al.*, [18, 19]. The deformation parameter values are taken from the tables by Moller *et al.*, [20, 21], and the Q values are taken from [22]. Tables 1 and 2 give the logarithmic half-lives for $^8_4$Be & $^{12}_6$C from $Z = 130$–136 isotopes including deformation effects. In the super heavy region, $Z = 114$ and $N = 184$, nuclei are expected to be doubly magic. The formation of the doubly magic daughter $^{298}114$ from different decaying parents with the emission of clusters will be the most favorable decay chain (Table 3). In Figs. 1 and 2, we present the comparison of computed logarithmic half-lives with and without deformation for $Z = 130$–136 with available data of UDL. Figure 3 shows the decay half-lifes for different cluster mass numbers (without and with deformation) of parent nuclei. The dips in the half-life curve suggest that the emission of certain clusters from the parent nuclei occurs rapidly

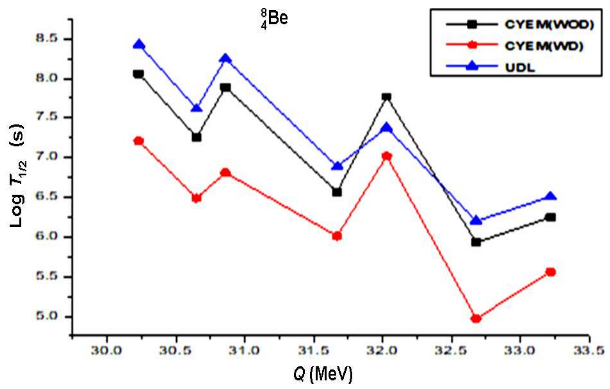

Fig. 1. Plot for Log$T_{1/2}$ (s) vs. Q (MeV) of $^{8}_{4}$Be cluster emitted from various parent nuclei

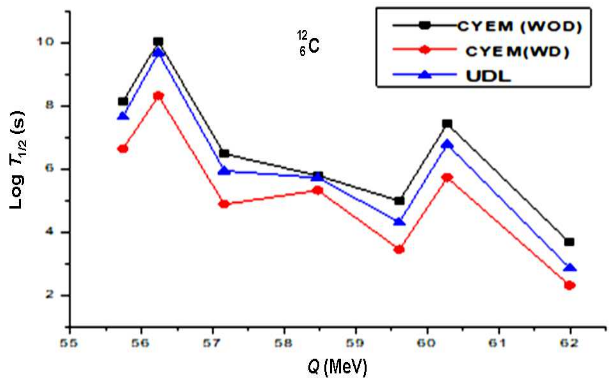

Fig. 2. Plot for Log$T_{1/2}$ (s) vs. Q (MeV) of $^{12}_{6}$C cluster emitted from various parent nuclei

Table 1. **Comparison of calculated logarithmic half life of $^{8}_{4}$Be for Z = 130–136 isotopes for the case of without and with deformations**

Parent nuclei	Q (MeV) [22]	Log $T_{1/2}$ (s)		
		Calculated		Reference
		CYEM (WOD)	CYEM (WD) ($\beta_{2P}, \beta_{4P}, \beta_{6P}, \beta_{2D}$)	UDL [18]
^{330}130	30.23	8.06	7.21	8.43
^{332}130	30.65	7.26	6.49	7.62
^{334}130	29.86	8.59	7.92	8.99
^{336}130	28.90	10.30	9.36	10.76
^{338}130	27.89	12.20	11.12	12.74
^{340}130	26.86	14.25	13.79	14.87
^{330}132	30.58	8.57	7.98	8.95
^{332}132	31.12	7.57	7.01	7.90
^{334}132	31.67	6.57	6.01	6.89
^{336}132	30.86	7.89	6.81	8.25
^{338}132	29.91	9.51	8.84	9.96
^{340}132	28.90	11.34	10.93	11.85
^{330}134	32.38	6.61	6.10	6.88
^{332}134	31.37	7.77	7.02	7.38
^{334}134	32.03	5.93	4.97	6.20
^{336}134	32.68	7.18	6.79	7.51
^{338}134	31.88	8.73	8.26	9.13
^{340}134	30.94	10.45	9.38	10.92
^{330}136	34.34	4.58	4.11	4.75
^{332}136	33.22	6.26	6.25	6.51
^{334}136	32.24	7.80	7.23	8.11
^{336}136	33.01	6.47	5.86	6.74
^{338}136	33.78	5.18	4.83	5.40
^{340}136	33.00	6.35	5.89	6.63

Table 2. **Comparison of calculated logarithmic half life of $^{12}_{6}$C for Z = 130–136 isotopes for the case of without and with deformations**

Parent nuclei	Q (MeV) [22]	Log $T_{1/2}$ (s)		
		Calculated		Reference
		CYEM (WOD)	CYEM (WD) ($\beta_{2P}, \beta_{4P}, \beta_{6P}, \beta_{2D}$)	UDL [18]
^{290}130	57.16	6.50	4.90	5.96
^{292}130	55.74	8.17	6.66	7.68
^{294}130	54.56	9.58	8.96	9.15
^{296}130	54.05	10.14	9.69	9.75
^{298}130	53.94	10.18	9.71	9.82
^{290}132	59.61	5.01	3.47	4.33
^{292}132	58.13	6.66	6.07	6.05
^{294}132	56.75	8.25	7.74	7.71
^{296}132	55.62	9.58	8.83	9.10
^{298}132	55.22	9.99	9.15	9.54
^{290}134	61.99	3.69	2.33	2.89
^{292}134	60.51	5.26	4.98	4.53
^{294}134	59.08	6.84	6.11	6.18
^{296}134	57.75	7.72	7.09	7.75
^{298}134	56.69	8.62	8.03	9.03
^{318}134	58.49	6.26	5.76	5.79
^{320}134	58.47	6.18	5.34	5.74
^{322}134	58.02	6.63	5.84	6.21
^{324}134	57.02	7.79	7.13	7.41
^{318}136	59.90	5.96	5.07	5.42
^{320}136	60.02	5.72	4.99	5.19
^{322}136	59.82	5.85	5.05	5.34
^{324}136	59.18	6.53	5.79	6.05
^{326}136	57.99	7.90	6.87	7.48
^{328}136	56.24	10.04	8.34	9.70

Table 3. **Alpha and cluster decay of SHN leading to the formation of doubly magic daughter nucleus $^{298}114$**

Parent nuclei	Emitted cluster	Daughter nuclei	Q (MeV) [22]	Log $T_{1/2}$ (s)				Branching ratio
				CYEM				
				With out deformation	With deformation ($\beta_{2P}, \beta_{4P}, \beta_{6P}$)	UDL [19]	Alpha decay	
$^{302}116$	^{4}He	$^{298}114$	12.08	–3.84	–3.61	–4.06	–3.84	1
$^{304}117$	^{6}Li	$^{298}114$	9.81	34.82	34.71	35.06	–5.76	–39.20
$^{307}118$	^{9}Be	$^{298}114$	22.67	20.38	20.31	20.01	–5.09	–23.11
$^{308}118$	^{10}Be	$^{298}114$	23.47	19.61	18.84	19.86	–3.91	–22.41
$^{310}120$	^{12}C	$^{298}114$	43.97	18.89	18.76	16.64	–1.11	–19.24
$^{312}120$	^{14}C	$^{298}114$	46.19	15.42	15.11	15.16	–0.94	–9.01
$^{314}122$	^{16}O	$^{298}114$	64.12	20.76	20.61	19.81	–4.83	–24.69
$^{316}122$	^{18}O	$^{298}114$	66.63	18.93	18.75	17.73	–4.29	–21.09
$^{318}122$	^{20}O	$^{298}114$	66.74	17.71	17.66	18.95	–3.18	–16.12
$^{318}124$	^{20}Ne	$^{298}114$	81.94	26.49	26.04	26.33	–6.04	–36.03
$^{320}124$	^{22}Ne	$^{298}114$	87.36	20.11	20.00	20.06	–5.50	–32.91
$^{322}124$	^{24}Ne	$^{298}114$	90.47	16.83	16.61	16.78	–4.37	–20.10
$^{324}124$	^{26}Ne	$^{298}114$	88.60	22.90	22.81	20.19	–1.74	–23.20
$^{322}126$	^{24}Mg	$^{298}114$	97.22	32.47	30.11	35.99	15.11	–13.26
$^{323}126$	^{25}Mg	$^{298}114$	98.88	30.96	30.81	34.28	18.20	–8.15
$^{324}126$	^{26}Mg	$^{298}114$	104.12	27.15	26.03	27.52	19.60	2.28
$^{326}126$	^{28}Mg	$^{298}114$	112.05	18.44	18.40	17.91	–2.29	–20.81
$^{326}128$	^{28}Si	$^{298}114$	118.59	36.10	35.68	36.61	–5.49	–33.36
$^{327}128$	^{29}Si	$^{298}114$	120.31	35.04	34.27	34.81	–5.27	–25.78
$^{328}128$	^{30}Si	$^{298}114$	125.49	26.12	25.52	28.44	–5.41	–27.00
$^{329}129$	^{31}P	$^{298}114$	132.16	31.89	31.59	33.61	–5.25	–28.79
$^{330}130$	^{32}S	$^{298}114$	144.54	34.91	34.52	31.51	–14.87	–48.52
$^{331}130$	^{33}S	$^{298}114$	146.99	27.12	26.12	28.83	–15.00	–27.21
$^{332}130$	^{34}S	$^{298}114$	151.79	22.79	22.40	23.36	–14.22	–36.51
$^{333}131$	^{35}Cl	$^{298}114$	158.08	28.14	27.75	28.74	–15.51	–39.09
$^{334}132$	^{36}Ar	$^{298}114$	165.55	33.16	32.30	32.66	–5.79	–31.06
$^{336}132$	^{38}Ar	$^{298}114$	174.65	21.72	21.19	22.52	–6.59	–31.12
$^{338}132$	^{40}Ar	$^{298}114$	180.35	18.14	15.11	16.28	–6.09	–26.11
$^{338}134$	^{40}Ca	$^{298}114$	188.67	30.64	30.08	31.18	–6.87	–41.38

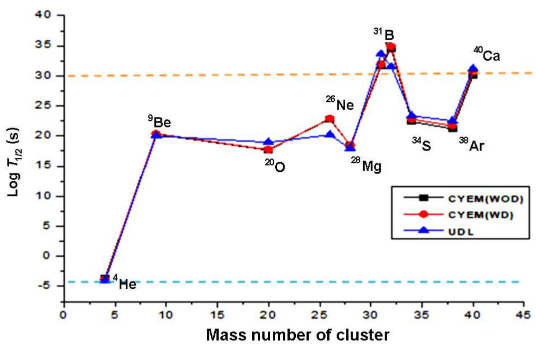

Fig. 3. Decay half-life of different clusters versus Mass number of clusters (without deformation and with deformation) of parent nuclei. The dashed lines represent the experimental observation limits $10^{-6} \le T_{1/2} \le 10^{30}$ s

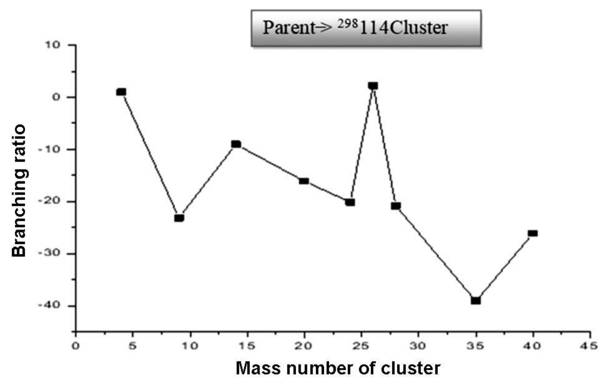

Fig. 4. The cluster decay leading to doubly magic daughter in super heavy region

and are relatively favorable compared to the nearby clusters. The dashed lines represent the experimental observation limits $10^{-6} \leq T_{1/2} \leq 10^{30}$ s. Figure 4 shows the cluster decay leading to doubly magic daughter in super heavy region. Among the lighter clusters, ^{14}C, ^{20}O and ^{26}Mg exhibit lower decay half-lives, and among the medium clusters, ^{33,34}Si and ^{40}Ar exhibit lower half-life values. The branching ratio is higher for these clusters. Depending on the branching ratio, some of these rare cluster decays may occur and can be identified during the synthesis or decay-related experiments in the near future.

6. Conclusions

Using the CYE model, we have predicted the cluster decay half-lifetimes for ^{8}Be & ^{12}C emission from different super heavy parent nuclei $Z = 130$–136. The computed half-life values are compared with available data. They are in good agreement with each other. When deformation effects are included, half-life values are found to be decreased, because it reduces the height and width of the barrier. Again most desirable decay chain is chosen such that it leads to the doubly magic daughter ^{298}114 from decaying parents with different cluster emission and their decay properties are studied and is compared with the UDL model. The branching ratio relative to the alpha decay has also been calculated. The presented results provide the useful information and knowledge for improving theoretical models and possible future experimental studies on super heavy nucleus.

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Received 21.03.24

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ДОСЛІДЖЕННЯ КЛАСТЕРНИХ РОЗПАДІВ, ЗОКРЕМА ТИХ, ЩО ДАЮТЬ ПОДВІЙНО МАГІЧНЕ ЯДРО ^{298}114, ТА КОЕФІЦІЄНТІВ РОЗГАЛУЖЕННЯ ВІДНОСНО α-РОЗПАДУ

Дослідження надважких ядер і властивостей їх розпаду є однією з галузей ядерної фізики, що швидко розвивається. Використовуючи CYE модель та враховуючи деформації розпадного ядра, ми досліджуємо кластерні розпади надважких ядер (Z = 130–136) з утворенням кластерів $^{8}_{4}$Be та $^{12}_{6}$C. Крім того, розглянуто випадок утворення подвійно магічного дочірнього кластера ^{298}114 з різних розпадних ядер. Розраховані часи напіврозпаду добре узгоджуються з результатами інших моделей. Також розраховано коефіцієнти розгалуження відносно α-розпаду.

Ключові слова: час напіврозпаду, Q-фактор, деформація, подвійно магічні ядра, коефіцієнт розгалуження.