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Theoretical studies on the fine structure of α decay for even–odd and even–even isotopes of Cm, Cf, Fm and No nuclei

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Abstract. Using the cubic plus Yukawa plus exponential model (CYEM), half-lives of α decay from the ground state of the parent nuclei to the ground state of the daughter nuclei and from the ground state to an excited state of the daughter nuclei have been systematically investigated for even–odd and even–even isotopes of Cm, Cf, Fm and No nuclei by incorporating centrifugal potential term, rotational energy term, deformation effects (β_2 and β_4) of the parent and daughter nuclei and spin–parity effects. We have done our calculations by considering the Coulomb, centrifugal and Yukawa plus exponential potentials as an interacting barrier for separated fragments and the cubic potential for the overlapping region. The calculated half-lives are compared with the available data. Our results are found to be in good agreement with each other. The effect of the centrifugal potential on half-life was evaluated. The branching ratio, hindrance factor and standard deviation of half-lives from the ground state of the parent nuclei to the ground state of the daughter nuclei have been calculated.

Keywords. Q-value; α decay; fine structure.

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1. Introduction

α Decay can provide reliable information on the ground-state energy, ground-state half-life, nuclear spin–parity, nuclear deformation, nuclear clustering, shell effect and nuclear interactions. The α decay theory was formulated by Gamow [1] and independently by Gurney and Condon based on quantum tunnelling. The α-particles are supposed to be pre-formed within the nucleus and emitted by tunnelling through the potential barrier. The α decay to several different excited states of the daughter nucleus is called fine structure. The fine structure of α decay was formulated by Rosenblum [2] in 1929. Many theoretical models have been employed to study such α fine structures [3–15]. To study such α decay, we have developed a cubic plus Yukawa plus exponential model (CYEM) [16] in two-sphere approximation, in which the zero-point vibration energy is explicitly included without violating the conservation of energy and the nuclear inertia mass coefficient which is dependent on the centre of mass distance, has been used. We have already calculated the half-lives of α decay from the ground state of the parent nuclei to the ground state of the daughter nuclei and the fine structure of α decay for some trans-actinide nuclei [17–21] without including the rotational energy term. In the present work, we have done our calculations by considering the Coulomb, centrifugal, rotational and Yukawa plus exponential potentials as an interacting barrier for separated fragments and the cubic potential for the overlapping region described in §2. The results and discussion are given in §3. Finally, the conclusions are given in §4.

2. Cubic plus Yukawa plus exponential model

The half-lives of the parent nuclei decaying via α emission are calculated using the CYEM. The parent and the daughter nuclei are considered to be spheroid, keeping the emitted cluster as spherical. If the daughter nucleus has a deformation, say quadruple deformation only, and if the potentials are measured from the Q-value of the reaction, then the potential for the post-scission region as a function of the centre of mass distance r of the fragment is given by

$$V(r) = V_C(r) + V_n(r) + V_{\rm rot} + \frac{\ell(\ell+1)\hbar^2}{2\mu r^2} - V_{\rm df}(r) - Q, \quad r \geq r_t, \tag{1}$$

where $r_t = a_e + R_d$, a_e is the semimajor (or) semiminor axis of the spheroidal cluster depending on the prolate or oblate shape of the emitted cluster, R_d is the surface radius of a spheroidal daughter nucleus, V_C is the Coulomb potential between a spheroidal daughter and spherical emitted cluster as in ref. [22], V_n is the nuclear interaction energy due to finite range effects of Krappe *et al* [23], $V_{\rm df}$ is the change in nuclear interaction energy due to quadruple deformations in the daughter nuclei as in ref. [23], $V_{\rm rot}$ is the rotational energy term, r is the distance between fragment centres, ℓ is the angular momentum and μ is the reduced mass of the system.

The Coulomb potential is taken as the interaction between the spheroidal daughter nucleus and the spherical emitted cluster. For a prolate spheroidal daughter nucleus with longer axis along the fission direction, Pik-Pichak [22] obtained

$$V_C(r) = \frac{3}{2}\frac{Z_d Z_e e^2 \gamma}{r}\left\{\frac{1-\gamma^2}{2}\ln\frac{\gamma+1}{\gamma-1} + \gamma\right\}. \tag{2}$$

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

$$V_C(r) = \frac{3}{2}\frac{Z_d Z_e e^2}{r}\left\{\gamma\left(1+\gamma^2\right)\arctan\gamma^{-1} - \gamma^2\right\}, \tag{3}$$

where

$$\gamma = \frac{r}{\left(a_e^2 - b_e^2\right)^{1/2}}$$

with Z_d and Z_e being the atomic numbers of the daughter nucleus and the emitted cluster, respectively, and a_e and b_e are the semimajor and semiminor axes of the spherical emitted cluster.

For two separated spherical nuclei of equivalent sharp surface radii R_d and R_e, the nuclear interaction energy V_n of Krappe *et al* [23] is given by

$$V_n = -D\left[F + \frac{r - r_{12}}{a}\right]\frac{r_{12}}{r}\exp\left[\frac{r_{12} - r}{a}\right],$$
$$r_{12} = R_d + R_e. \tag{4}$$

Depth constant D is given by

$$D = \frac{4a^3 g(R_d/a) g(R_e/a) e^{-r_{12}/a}}{r_0^2 r_{12}} C_s', \tag{5}$$

where

$$g(X) = X\cosh x - \sinh x. \tag{6}$$

For the case of two separated nuclei

$$C_s' = [C_s(d)C_s(e)]^{1/2}. \tag{7}$$

The constant F is given by

$$F = 4 + \frac{r_{12}}{a} - \frac{f(R_d/a)}{g(R_d/a)} - \frac{f(R_e/a)}{g(R_e/a)}, \tag{8}$$

where

$$f(x) = X^2\sinh x. \tag{9}$$

Also,

$$R_i = r_o A_i^{1/3}, \tag{10}$$

$$C_s(i) = a_s\left(1 - K_s I_i^2\right) \tag{11}$$

and

$$I_i = \frac{(N_i - Z_i)}{A_i} \quad (i = d, e). \tag{12}$$

The energy of an α-particle emitted from the nucleus in the α decay is

$$Q = Q_{\rm g.s\to g.s} - E_i^*, \tag{13}$$

where $Q_{\rm g.s\to g.s}$ is the Q-value for a ground state to ground state transition and E_i^* is the excitation energy of the daughter nucleus to the ith state taken from ref. [24]. The ground state to ground state Q-value is given by

$$Q_{\rm g.s\to g.s} = \Delta M_p - (\Delta M_d + \Delta M_\alpha) + \left[k_1\left(Z_p^{\varepsilon_1} - Z_d^{\varepsilon_1}\right) - k_2 Z_c^{\varepsilon_2}\right],$$

where ΔM_p, ΔM_d and ΔM_α are the excess mass of the parent, daughter and α nuclei, respectively, as tabulated by Audi *et al* [25]. The terms in the brackets represent the effect of the screening to the nucleus caused by the surrounding electrons. The quantity kZ^ε represents the total binding energy of the Z-electrons in the atom, where the values $k_1 = 8.7 \times 10^{-6}$ MeV and $\varepsilon_1 = 2.517$ for nuclei with $Z \geq 60$ and $k_2 = 13.6 \times 10^{-6}$ MeV and $\varepsilon_2 = 2.408$ for $Z < 60$ have been found from Huang *et al* [26].

For the overlapping region, we approximate the potential barrier by a third-order polynomial in terms of (r) having the form [27]

$$V(r) = -E_v + [V(r_t) + E_v]\left\{S_d\left(\frac{r - r_i}{r_t - r_i}\right)^2 - S_e\left(\frac{r - r_i}{r_t - r_i}\right)^3\right\}, \quad r_i \leq r \leq r_t, \tag{14}$$

Table 1. Logarithmic half-lives of α decay for even–odd isotopes of Cm, Cf, Fm and No nuclei from the ground state of the parent nuclei to the ground state of the daughter nuclei.

Decay mode	Q (MeV)	$\ell_{\text{min.}}(\hbar)$	$\log_{10}T_{1/2}$ (s)				$\log \text{HF}_{\text{cal}}$.
			CYEM	UMADAC [32]	Mollar *et al* [31]	Expt. [24]	
$^{233}\text{Cm} \rightarrow {}^{229}\text{Pu} + \alpha$	7.52	0	2.01	2.58	2.12	–	–
$^{235}\text{Cm} \rightarrow {}^{231}\text{Pu} + \alpha$	7.34	2	2.80	3.58	3.33	–	–
$^{237}\text{Cm} \rightarrow {}^{233}\text{Pu} + \alpha$	6.82	0	4.73	5.09	4.79	–	–
$^{239}\text{Cm} \rightarrow {}^{235}\text{Pu} + \alpha$	6.59	1	5.82	7.92	5.96	–	–
$^{241}\text{Cm} \rightarrow {}^{237}\text{Pu} + \alpha$	6.23	3	7.85	9.93	7.90	6.45	0.822
$^{243}\text{Cm} \rightarrow {}^{239}\text{Pu} + \alpha$	6.21	2	7.74	8.12	9.99	8.96	1.158
$^{245}\text{Cm} \rightarrow {}^{241}\text{Pu} + \alpha$	5.67	2	10.71	11.19	12.62	–	–
$^{247}\text{Cm} \rightarrow {}^{243}\text{Pu} + \alpha$	5.40	1	12.30	14.66	14.82	15.55	1.264
$^{249}\text{Cm} \rightarrow {}^{245}\text{Pu} + \alpha$	5.19	5	14.65	15.85	13.52	–	–
$^{251}\text{Cm} \rightarrow {}^{247}\text{Pu} + \alpha$	5.16	0	13.84	13.74	12.25	–	–
$^{239}\text{Cf} \rightarrow {}^{235}\text{Cm} + \alpha$	7.86	0	1.48	2.03	2.33	–	–
$^{241}\text{Cf} \rightarrow {}^{237}\text{Cm} + \alpha$	7.70	1	2.08	4.42	4.02	–	–
$^{243}\text{Cf} \rightarrow {}^{239}\text{Cm} + \alpha$	7.46	3	3.38	5.74	5.88	–	–
$^{245}\text{Cf} \rightarrow {}^{241}\text{Cm} + \alpha$	7.30	0	3.58	4.12	6.92	3.43	0.958
$^{247}\text{Cf} \rightarrow {}^{243}\text{Cm} + \alpha$	6.54	2	7.14	7.38	8.12	–	–
$^{249}\text{Cf} \rightarrow {}^{245}\text{Cm} + \alpha$	6.34	1	8.03	10.34	9.77	10.05	1.252
$^{251}\text{Cf} \rightarrow {}^{247}\text{Cm} + \alpha$	6.22	5	9.98	11.30	9.58	10.45	1.047
$^{253}\text{Cf} \rightarrow {}^{249}\text{Cm} + \alpha$	6.17	4	9.66	9.67	8.15	–	–
$^{255}\text{Cf} \rightarrow {}^{251}\text{Cm} + \alpha$	5.78	4	11.86	11.92	12.36	–	–
$^{245}\text{Fm} \rightarrow {}^{241}\text{Cf} + \alpha$	8.48	3	0.57	2.66	2.83	–	–
$^{247}\text{Fm} \rightarrow {}^{243}\text{Cf} + \alpha$	8.30	3	1.19	1.52	3.40	–	–
$^{249}\text{Fm} \rightarrow {}^{245}\text{Cf} + \alpha$	7.76	4	3.43	3.03	4.79	–	–
$^{251}\text{Fm} \rightarrow {}^{247}\text{Cf} + \alpha$	7.47	2	4.09	6.24	7.06	7.85	1.919
$^{253}\text{Fm} \rightarrow {}^{249}\text{Cf} + \alpha$	7.24	5	5.89	7.47	5.81	8.22	1.396
$^{255}\text{Fm} \rightarrow {}^{251}\text{Cf} + \alpha$	7.29	4	5.40	5.41	5.77	–	–
$^{257}\text{Fm} \rightarrow {}^{253}\text{Cf} + \alpha$	6.91	2	6.60	7.01	8.36	6.94	1.052
$^{259}\text{Fm} \rightarrow {}^{255}\text{Cf} + \alpha$	6.52	2	8.46	8.93	11.46	–	–
$^{251}\text{No} \rightarrow {}^{247}\text{Fm} + \alpha$	8.80	2	0.22	0.11	1.28	–	–
$^{253}\text{No} \rightarrow {}^{249}\text{Fm} + \alpha$	8.46	1	1.19	3.51	2.77	–	–
$^{255}\text{No} \rightarrow {}^{251}\text{Fm} + \alpha$	8.48	5	2.18	3.62	1.54	4.20	1.160
$^{257}\text{No} \rightarrow {}^{253}\text{Fm} + \alpha$	8.52	1	1.045	1.71	2.51	1.389	1.329
$^{259}\text{No} \rightarrow {}^{255}\text{Fm} + \alpha$	7.93	2	3.31	3.69	4.03	–	–

where r_i is the distance between the centres of masses of the daughter nucleus and the emitted particle. C_{d} and C_{e} are the central radii of the fragments [28] and μ is the reduced mass of the system. The expression for E_v is given by [29]

$$E_v = \frac{\pi\hbar}{2}\frac{[2Q/\mu]^{1/2}}{(C_{\text{d}} + C_{\text{e}})}, \tag{15}$$

$$C_i = 1.18\, A_i^{1/3} - 0.48 \quad (i = \text{d}, \text{e}), \tag{16}$$

$$\mu = \frac{mA_{\text{d}}A_{\text{e}}}{A}, \tag{17}$$

where m is the nucleon mass, μ is the reduced mass of the system and A_{d} and A_{e} are the mass numbers of the daughter and emitted cluster, respectively.

If the nuclei have spheroidal 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 ref. [23]:

$$R(\theta) = R_0\left[1 + \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \beta_{nm}Y_{nm}(\theta)\right]. \tag{18}$$

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

If we consider spheroidal deformation $\beta_{2,}$ then

$$R(\theta) = R_0\left[1 + \beta_2\left(\frac{5}{4\pi}\right)^{1/2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)\right] \tag{19}$$

Table 2. Logarithmic half-lives of α decay for even–even isotopes of Cm, Cf, Fm and No nuclei from the ground state of the parent nuclei to ground state of the daughter nuclei.

Decay mode	Q (MeV)	$\ell_{\text{min.}}(\hbar)$	$\log_{10}T_{1/2}$ (s)				$\log \text{HF}_{\text{cal.}}$
			CYEM	UMADAC [32]	Mollar *et al* [31]	Expt. [24]	
$^{234}\text{Cm} \rightarrow {}^{230}\text{Pu} + \alpha$	7.321	0	2.75	2.27	1.47	–	–
$^{236}\text{Cm} \rightarrow {}^{232}\text{Pu} + \alpha$	7.023	0	3.88	3.23	3.28	–	–
$^{238}\text{Cm} \rightarrow {}^{234}\text{Pu} + \alpha$	6.926	0	4.28	5.26	4.52	5.51	1.287
$^{240}\text{Cm} \rightarrow {}^{236}\text{Pu} + \alpha$	6.353	0	6.86	6.29	5.81	6.52	0.950
$^{242}\text{Cm} \rightarrow {}^{238}\text{Pu} + \alpha$	6.171	0	7.74	6.86	7.52	7.28	0.941
$^{244}\text{Cm} \rightarrow {}^{240}\text{Pu} + \alpha$	5.858	0	9.45	8.57	10.21	8.87	0.939
$^{246}\text{Cm} \rightarrow {}^{242}\text{Pu} + \alpha$	5.431	0	11.99	11.10	13.05	11.26	0.939
$^{248}\text{Cm} \rightarrow {}^{244}\text{Pu} + \alpha$	5.117	0	14.06	13.14	14.78	13.16	0.936
$^{250}\text{Cm} \rightarrow {}^{246}\text{Pu} + \alpha$	5.125	0	14.05	13.48	10.87	–	–
$^{238}\text{Cf} \rightarrow {}^{234}\text{Cm} + \alpha$	8.086	0	0.77	0.59	1.01	–	–
$^{240}\text{Cf} \rightarrow {}^{236}\text{Cm} + \alpha$	7.666	0	2.19	1.75	1.87	2.03	1.086
$^{242}\text{Cf} \rightarrow {}^{238}\text{Cm} + \alpha$	7.472	0	2.95	2.52	3.28	–	–
$^{244}\text{Cf} \rightarrow {}^{240}\text{Cm} + \alpha$	7.284	0	3.68	2.88	5.01	–	–
$^{246}\text{Cf} \rightarrow {}^{242}\text{Cm} + \alpha$	6.817	0	5.69	5.19	6.80	4.21	0.40
$^{248}\text{Cf} \rightarrow {}^{244}\text{Cm} + \alpha$	6.316	0	8.10	7.19	7.92	7.56	0.933
$^{250}\text{Cf} \rightarrow {}^{246}\text{Cm} + \alpha$	6.083	0	9.33	8.45	9.97	8.69	0.931
$^{252}\text{Cf} \rightarrow {}^{248}\text{Cm} + \alpha$	6.172	0	8.89	12.14	7.99	–	–
$^{242}\text{Fm} \rightarrow {}^{238}\text{Cf} + \alpha$	8.648	0	−0.35	0.17	2.52	–	–
$^{244}\text{Fm} \rightarrow {}^{240}\text{Cf} + \alpha$	8.507	0	0.08	0.87	−0.24	–	–
$^{246}\text{Fm} \rightarrow {}^{242}\text{Cf} + \alpha$	8.333	0	0.63	2.24	0.31	0.17	0.269
$^{248}\text{Fm} \rightarrow {}^{244}\text{Cf} + \alpha$	7.948	0	1.99	2.91	1.55	1.66	0.834
$^{250}\text{Fm} \rightarrow {}^{246}\text{Cf} + \alpha$	7.509	0	3.66	4.66	3.26	3.38	0.923
$^{252}\text{Fm} \rightarrow {}^{248}\text{Cf} + \alpha$	7.106	0	5.35	6.36	4.97	5.04	0.942
$^{254}\text{Fm} \rightarrow {}^{250}\text{Cf} + \alpha$	7.260	0	4.72	3.85	4.08	4.14	0.877
$^{256}\text{Fm} \rightarrow {}^{252}\text{Cf} + \alpha$	6.980	0	6.01	4.46	5.27	5.14	0.855
$^{258}\text{Fm} \rightarrow {}^{254}\text{Cf} + \alpha$	6.615	0	7.87	8.61	7.26	–	–
$^{260}\text{Fm} \rightarrow {}^{256}\text{Cf} + \alpha$	6.258	0	9.60	12.54	9.76	–	–
$^{248}\text{No} \rightarrow {}^{244}\text{Fm} + \alpha$	9.177	0	−1.22	−0.78	−1.49	–	–
$^{250}\text{No} \rightarrow {}^{246}\text{Fm} + \alpha$	8.898	0	−0.36	−0.32	−0.69	–	–
$^{252}\text{No} \rightarrow {}^{248}\text{Fm} + \alpha$	8.499	0	0.94	1.19	0.59	0.74	0.787
$^{254}\text{No} \rightarrow {}^{250}\text{Fm} + \alpha$	8.179	0	2.06	2.49	1.74	1.82	0.883
$^{256}\text{No} \rightarrow {}^{252}\text{Fm} + \alpha$	8.533	0	0.87	0.44	0.54	0.53	0.609
$^{258}\text{No} \rightarrow {}^{254}\text{Fm} + \alpha$	8.103	0	2.44	1.30	2.04	–	–
$^{260}\text{No} \rightarrow {}^{256}\text{Fm} + \alpha$	7.649	0	4.14	5.29	3.75	–	–
$^{262}\text{No} \rightarrow {}^{258}\text{Fm} + \alpha$	7.197	0	6.10	8.18	3.55	–	–
$^{264}\text{No} \rightarrow {}^{260}\text{Fm} + \alpha$	6.767	0	8.06	11.16	8.65	–	–

and if the Nilsson's hexadecapole deformation β_4 is also included in the deformation, then eq. (19) becomes

$$R(\theta) = R_0\left[1 + \beta_2\left(\frac{5}{4\pi}\right)^{1/2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + \beta_4\left(\frac{9}{4\pi}\right)^{1/2}\frac{1}{8}\left(35\cos^4\theta - 30\cos^2\theta + 3\right)\right]. \tag{20}$$

Expressing the energies in MeV, lengths in fm and time in s for calculating the half-life of the decay system we use the formula

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

The action integral K is given by $K = K_{\text{L}} + K_{\text{R}}$, where

$$K_{\text{L}} = \frac{2}{\hbar}\int_{r_a}^{r_t}[2B_r(r)V(r)]^{1/2}\,\mathrm{d}r, \tag{22}$$

$$K_{\text{R}} = \frac{2}{\hbar}\int_{r_t}^{r_b}[2B_r(r)V(r)]^{1/2}\,\mathrm{d}r. \tag{23}$$

Here, $B_r(r)$ is the nuclear inertial mass coefficient with respect to r associated with the motion in the fission direction. The limits of integration r_a and r_b are the two appropriate zeros of the integrand which are found numerically.

3. Results and discussions

The half-lives of α decay for even–even and even–odd isotopes of Cm, Cf, Fm and No nuclei have been investigated by using the CYEM. We have done our calculations by including quadrupole and hexadecapole deformations in the parent nuclei along with the quadrupole deformation of daughter nuclei and spin–parity effects. The deformation values are taken from the tables of Möller *et al* [30]. The angular momentum carried by the α-particle in transition from ground state of the parent nuclei to the ground state of the daughter nuclei of even–even nucleus is zero. In even–odd, odd–even or odd–odd nuclei, it could not be equal to zero. The minimum values of possible angular momentum are included in our calculations. The values of natural angular momentum have been obtained from the usual nuclear spin and parity conservation law:

$$|J_i - J_j| \le l_\alpha \le |J_i + J_j| \quad \text{and} \quad \frac{\pi_i}{\pi_j} = (-1)^{l_\alpha},$$

where J_i and π_i are the spin and parity values of the parent nucleus and J_j and π_j are the spin and parity values of the daughter nucleus.

We have a parity selection rule, indicating which transitions are permitted and which are absolutely forbidden by conservation of parity. If the initial and final parities are the same, then l_α must be even, and if the parities are different, then l_α must be odd. For example, a $0 \to 3$ decay must have $l_\alpha = 3$, which must give a change in parity between initial and final states. Thus $0^+ \to 3^-$ is possible, but not $0^+ \to 3^+$. Similarly, $0^+ \to 2^-$, $0^+ \to 4^-$ decays cannot change the parity and so they are not permitted.

The logarithmic half-lives of α decay for some even–odd and even–even isotopes of Cm, Cf, Fm and No parent nuclei from the ground state of the parent nuclei to the ground state of the daughter nuclei have been calculated using the CYEM and presented in tables 1 and 2. The computed half-lives of α decay are compared with the theoretical values of Moeller *et al* [31], unified model for α decay and α capture proposed by Denisov and Khudenko [32] and experimental data [24]. The calculated half-lives are found to be in good agreement with the available data. Further, the decimal logarithmic half-lives of α decay from the ground state of the parent nuclei to the ground state of the daughter nuclei by incorporating spin–parity effects, rotational energy and deformation were plotted against the released energy (Q-value). These plots are shown in figures 1 and 2 and it can be seen that the present work is in better agreement with the available expermental and theoretical values.

The hindrance factor (HF) is calculated using the formula, $\mathrm{HF} = T_{1/2}^{\text{exp.}} / T_{1/2}^{\text{thero.}}$. If the deviation between the experimental half-lives and the theoretical half-lives for α decay is between 1 and 4, the transition is called a favoured transition. The logarithmic hindrance factor calculated for the transition from the ground state of the parent nuclei to the ground state of the daughter nuclei is found to be close to unity which shows a better result.

Then the effect of the centrifugal part of the potential on the half-life of α decay is evaluated and verification graph is given in figure 3. From this plot, it is found that as the angular momentum value increases, the decay rate slows down or the half-life value increases, because the height and width of the potential barrier increase with the inclusion of centrifugal potential. Poenaru *et al* [33] studied the centrifugal barrier effect on the lifetime of ^{151}Lu, ^{212}Po, ^{216}Rn, ^{223}Ra and ^{256}No for various charged particle emissions up to $\ell = 15$. Santhosh *et al* [34] pointed out that as the angular momentum increases, the decay becomes angular momentum hindered. Our results are very similar to the findings of Poenaru *et al* [33] and Santhosh *et al* [10]. Figure 4 represents the α transition from Cf^{245} parent nucleus to various excited levels of Cm^{243} daughter nucleus.

The half-lives of α decay from the ground state of the parent nuclei to various excited states of the daughter nuclei of the same isotopes are also evaluated using the CYEM and given in tables 3 and 4. The second and third columns in the corresponding tables show the transition between initial and final states of the nuclei. States without well-defined spin–parity values are mentioned in brackets. The state for which the spin–parity is not yet known is denoted by a question mark and in calculation they are treated as favoured transitions. In tables 3 and 4, the experimental half-lives corresponding to different excited states of the daughter nuclei have been calculated using the experimental total half-life and the α decay intensity to the corresponding states taken from ref. [24]. The computed half-lives are compared with the experimental data and they are found to be in good agreement within two orders of magnitude.

The branching ratio of α decay to each state of the daughter nucleus has been evaluated as $B_i = \Gamma(Q_i, l_i)/\sum_n (Q_n, l_n) \times 100\%$, where the sum n is going over all states which can be populated during the α transition from the ground state of the parent nucleus. The α decay intensities (branching ratio) to various excited states are evaluated and compared with the experimental values. Some variation occurs between

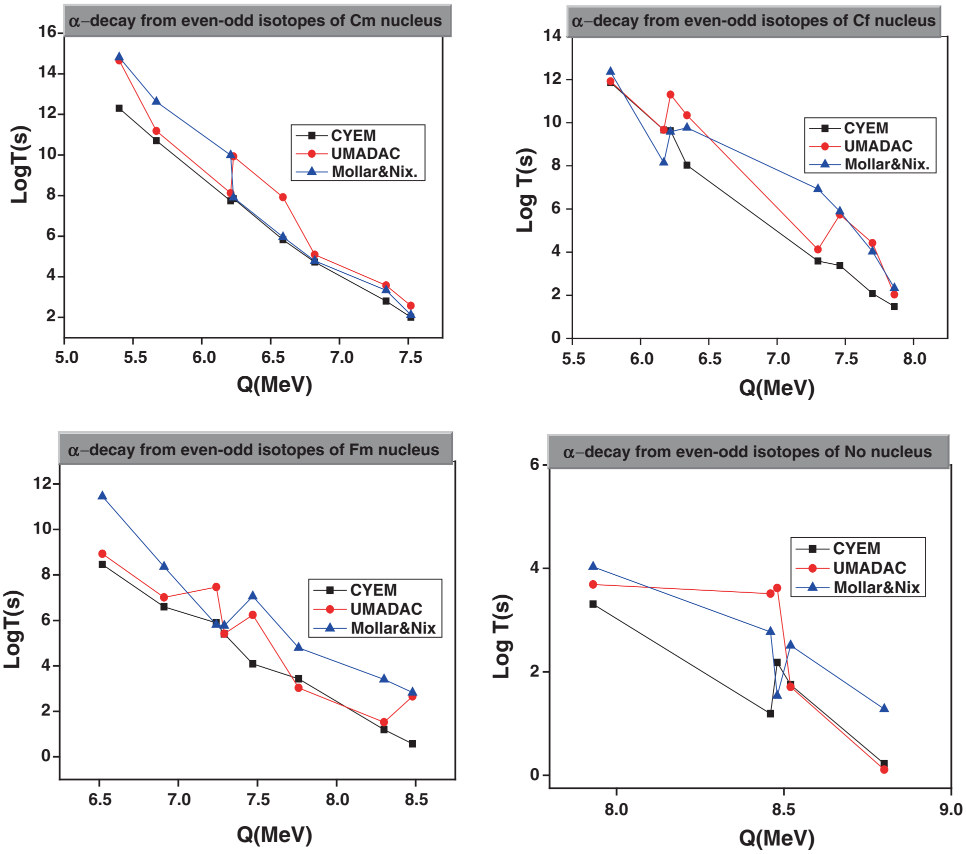

Figure 1. Logarithmic half-lives of α decay from the ground state of the parent nuclei to the ground state of the daughter nuclei against Q-values for even–odd isotopes.

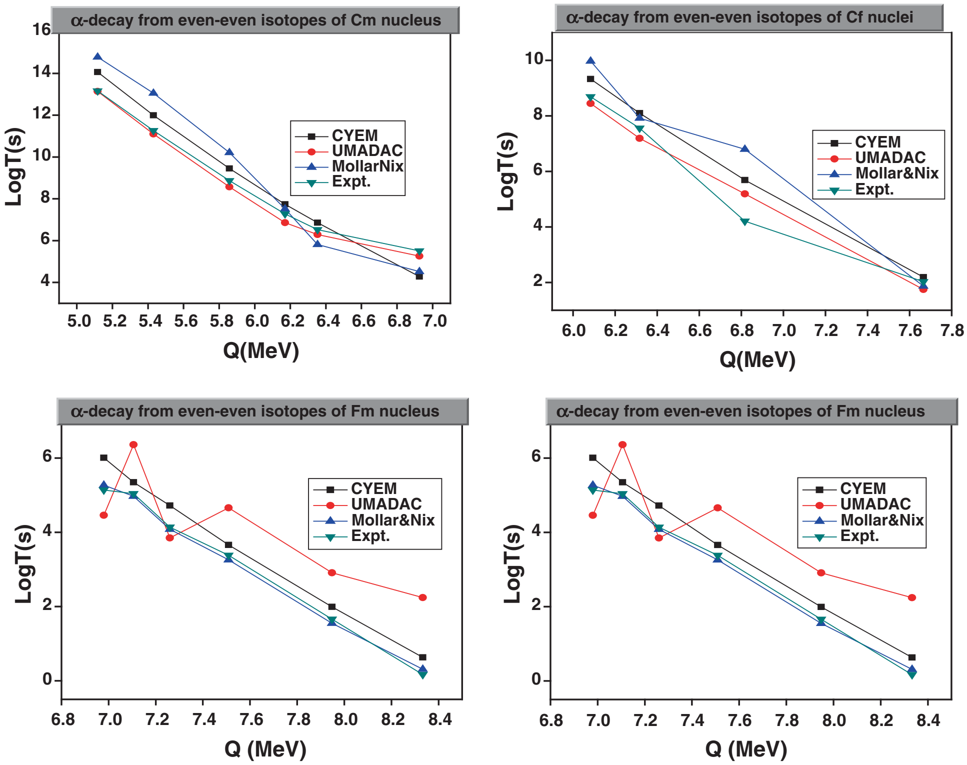

Figure 2. Logarithmic half-lives of α decay from the ground state of the parent nuclei to the ground state of the daughter nuclei against Q-values for even–even isotopes.

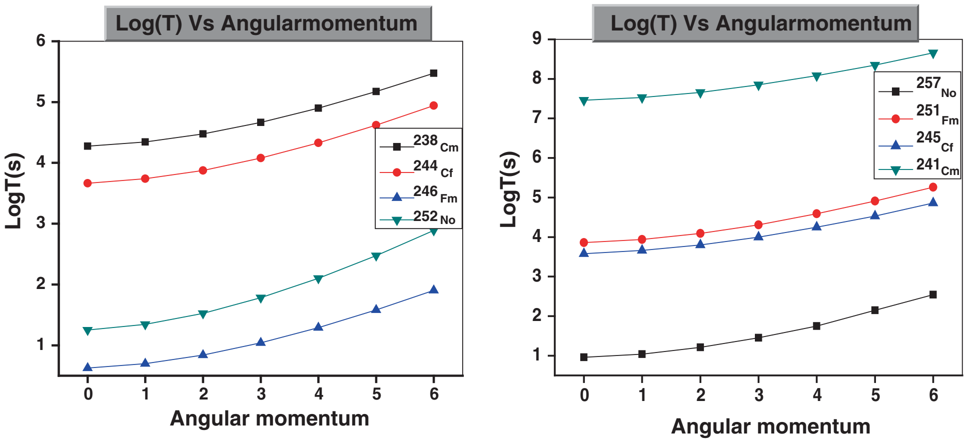

Figure 3. Plots of logarithmic half-lives of even–even and even–odd isotopes of Cm, Cf, Fm and No nuclei for α decays as a function of angular momentum values.

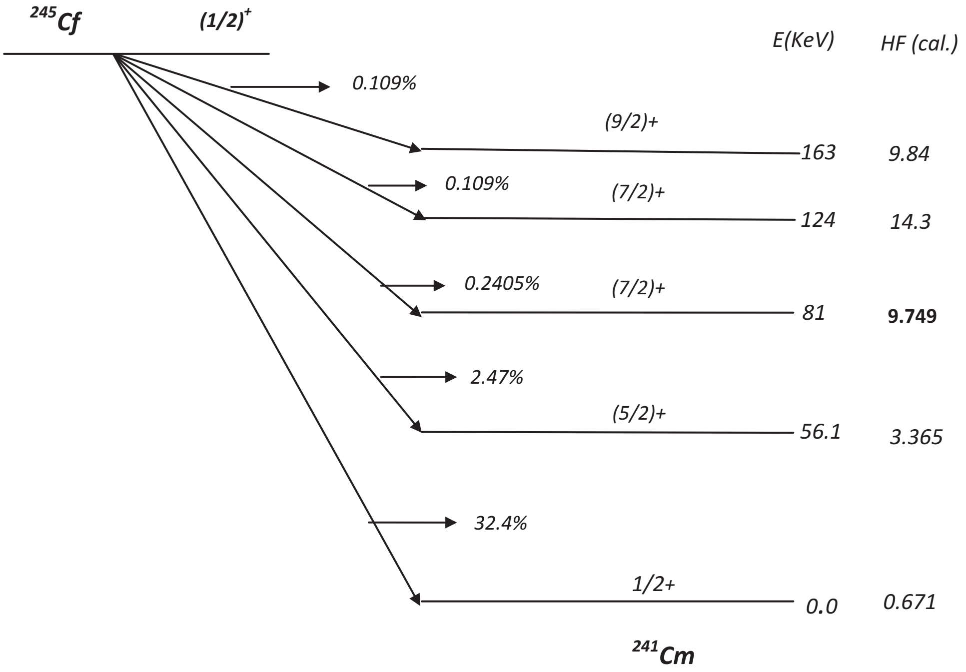

Figure 4. A schematic representation of α decay from the ground state of ^{245}Cf nucleus to a few levels of ^{241}Cm nucleus.

the experimental and the calculated values. The same results are obtained by other theoretical models also [7,8,11,34].

The even–even isotopes of Cm, Cf, Fm and No nuclei have the highest branching ratios for the $0^+ \rightarrow 0^+$ transition followed by the first excited state (see figure 5) and the hindrance factor corresponding to this transition is found to be very low. As we move to the other excited states, the branching ratio is found to be decreased with the increase of hindrance factor. Hence, the α decay to those excited states of the daughter nuclei are highly hindered, i.e., leading to unfavoured transition.

From table 3, we observe that in some decay mode of even–odd nuclei, the intensity of α transition to the other excited states is found to be greater than that of the ground state of the daughter nuclei. This is due to shell effects, internal structure of the parent and the daughter nuclei and odd parity effect [11].

The standard deviation is estimated using the following expression:

$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} [\log T_i^{\text{theor.}} - \log T_i^{\text{exp.}}]^2}.$$

Table 3. Logarithmic half-lives for α decay for even–odd isotopes of Cm, Cf, Fm and No nuclei from the ground state to the excited states of the daughter nuclei.

Transitions	I_i^π	I_f^π	$\ell_{\text{min.}}(\hbar)$	Q (MeV)	$\log_{10}T_{1/2}$ (s)		$\text{BR}_{\text{cal.}}(\%)$	$\text{BR}_{\text{expt.}}(\%)$
					CYEM	Expt.		
$^{241}\text{Cm} \rightarrow {}^{237}\text{Pu} + \alpha$	$1/2^+$	$7/2^+$	4	6.230	8.082	6.45	38.031	0.0015
	$1/2^+$	$9/2^-$	5	6.183	8.592	6.55	11.773	0.0012
	$1/2^+$	$11/2^-$	5	6.124	8.893	6.18	5.887	0.0028
	$1/2^+$	$1/2^+$	0	6.085	8.203	3.79	28.832	0.69
	$1/2^+$	$13/2^-$	7	6.059	9.857	6.55	0.639	0.0012
	$1/2^+$	$5/2^+$	2	6.029	8.696	4.55	9.266	0.118
	$1/2^+$	$7/2^+$	4	6.007	9.234	6.48	2.685	0.0014
	$1/2^+$	$9/2^+$	4	5.928	9.658	6.78	1.011	7×10^{-4}
	$1/2^+$	$3/2^+$	2	5.860	9.611	6.72	1.221	8×10^{-4}
	$1/2^+$	$5/2^+$	2	5.828	9.788	6.28	0.750	0.0022
$^{243}\text{Cm} \rightarrow {}^{239}\text{Pu} + \alpha$	$5/2^+$	$1/2^+$	2	6.210	7.745	8.95	29.142	1.50
	$5/2^+$	$3/2^+$	2	6.202	7.785	8.46	26.578	4.7
	$5/2^+$	$5/2^+$	0	6.153	7.832	9.10	23.852	1.097
	$5/2^+$	$7/2^+$	2	6.134	8.132	8.38	11.954	5.68
	$5/2^+$	$9/2^+$	2	6.046	8.591	10.14	4.154	0.099
	$5/2^+$	$11/2^+$	4	6.017	9.173	9.29	1.088	0.6980
	$5/2^+$	$5/2^+$	0	5.925	9.036	7.27	1.491	73
	$5/2^+$	$7/2^+$	2	5.880	9.484	8.08	0.532	11.5
	$5/2^+$	$9/2^+$	2	5.823	9.800	8.93	0.257	1.596
	$5/2^+$	$7/2^-$	1	5.818	9.695	9.84	0.327	0.1994
	$5/2^+$	$9/2^-$	3	5.776	10.254	9.99	0.090	0.1396
	$5/2^+$	$11/2^+$	4	5.748	10.650	10.66	0.036	0.030
	$5/2^+$	$1/2^-$	3	5.740	10.458	11.44	0.056	0.005
	$5/2^+$	$3/2^-$	1	5.718	10.262	11.18	0.089	0.0090
	$5/2^+$	?	0	5.711	10.234	11.30	0.095	0.0069
	$5/2^+$	$11/2^-$	3	5.723	10.555	10.86	0.045	0.0189
	$5/2^+$	$5/2^-$	0	5.704	10.274	11.30	0.086	0.0069
	$5/2^+$	?	0	5.672	10.460	11.86	0.056	0.0019
	$5/2^+$	?	0	5.607	10.841	11.29	0.023	0.0069
	$5/2^+$	$7/2^-$	1	5.654	10.633	11.86	0.038	0.0019
	$5/2^+$	?	0	5.464	11.705	11.67	3.195×10^{-3}	0.0029
	$5/2^+$	?	0	5.454	11.767	11.67	2.770×10^{-3}	0.0029
	$5/2^+$	?	0	5.447	11.810	12.14	2.509×10^{-3}	0.00099
	$5/2^+$	?	0	5.397	12.122	11.96	1.224×10^{-3}	0.0015
	$5/2^+$	?	0	5.360	12.355	12.54	7.153×10^{-4}	0.00039
$^{245}\text{Cm} \rightarrow {}^{241}\text{Pu} + \alpha$	$7/2^+$	$5/2^+$	2	5.670	10.708	11.42	38.588	0.58
	$7/2^+$	$7/2^+$	0	5.628	10.747	11.27	35.274	0.83
	$7/2^+$	$9/2^+$	2	5.574	11.274	12.59	10.482	0.04
	$7/2^+$	$11/2^+$	2	5.509	11.666	11.55	4.251	0.43
	$7/2^+$	$1/2^+$	4	5.508	12.110	12.89	1.529	0.0200
	$7/2^+$	$7/2^+$	0	5.495	11.544	9.22	5.629	93.2
	$7/2^+$	$9/2^+$	2	5.438	12.102	10.49	1.558	5
	$7/2^+$	?	0	5.409	12.077	12.34	1.650	0.07
	$7/2^+$	$11/2^+$	2	5.369	12.534	11.68	0.576	0.32
	$7/2^+$	$(1/2, 3/2)^+$	2	5.294	13.014	13.79	0.191	0.002
	$7/2^+$	?	0	5.286	12.860	13.89	0.272	0.0025
$^{247}\text{Cm} \rightarrow {}^{243}\text{Pu} + \alpha$	$9/2^-$	$7/2^+$	1	5.397	12.316	14.69	62.68	13.8
	$9/2^-$	$9/2^+$	1	5.338	12.690	15.077	26.49	5.7
	$9/2^-$	$11/2^+$	1	5.272	13.116	15.754	9.934	1.20
	$9/2^-$	$5/2^+$	3	5.109	14.552	15.532	0.364	2
	$9/2^-$	$7/2^+$	1	5.064	14.514	15.629	0.397	1.60

Table 3. *Continued.*

Transitions	I_i^π	I_f^π	$\ell_{\text{min.}}(\hbar)$	Q(MeV)	$\log_{10}T_{1/2}$ (s)		$\text{BR}_{\text{cal.}}(\%)$	$\text{BR}_{\text{expt.}}(\%)$
					CYEM	Expt.		
	$9/2^-$	$9/2^-$	2	4.994	15.147	13.982	0.092	71
	$9/2^-$	$11/2^-$	2	4.942	15.519	15.161	0.0393	4.7
$^{243}\text{Cf} \to {}^{239}\text{Cm} + \alpha$	$1/2^+$	$7/2^-$	3	7.460	3.377	2.81	44.159	–
	$1/2^+$	?	0	7.330	3.384	2.20	43.453	4.1
	$1/2^+$	$1/2^+$	0	7.220	3.929	1.81	12.388	9.9
$^{245}\text{Cf} \to {}^{241}\text{Cm} + \alpha$	$1/2^+$	$1/2^+$	0	7.295	3.603	3.43	62.156	32.4
	$1/2^+$	$(5/2^+)$	2	7.244	4.022	4.549	23.685	2.47
	$1/2^+$	$(7/2^{+)}$	4	7.219	4.573	5.562	6.659	0.240
	$1/2^+$	$(7/2^+)$	4	7.176	4.749	5.904	4.441	0.109
	$1/2^+$	$(9/2^+)$	4	7.137	4.911	5.904	3.058	0.109
$^{247}\text{Cf} \to {}^{243}\text{Cm} + \alpha$	$7/2^+$	$7/2^+$	0	6.445	7.411	5.530	76.309	0.033
	$7/2^+$	$9/2^+$	2	6.386	7.919	6.794	23.691	0.0018
$^{249}\text{Cf} \to {}^{245}\text{Cm} + \alpha$	$9/2^-$	$7/2^+$	1	6.340	8.031	10.04	59.235	2.460
	$9/2^-$	$9/2^+$	1	6.285	8.309	10.32	31.231	1.33
	$9/2^-$	$11/2^+$	1	6.218	9.652	10.90	1.418	0.346
	$9/2^-$	$13/2^+$	3	6.143	9.400	12.03	2.533	0.026
	$9/2^-$	$5/2^+$	3	6.087	9.616	9.92	1.540	3.33
	$9/2^-$	$7/2^+$	1	6.044	9.571	9.93	1.708	3.21
	$9/2^-$	$9/2^+$	1	5.989	9.870	10.28	0.858	1.43
	$9/2^-$	$9/2^-$	0	5.952	9.998	8.53	0.639	82.2
	$9/2^-$	$11/2^+$	1	5.923	10.234	11.03	0.371	0.26
	$9/2^-$	$11/2^-$	1	5.897	10.380	9.77	0.265	4.69
	$9/2^-$	$13/2^+$	3	5.842	11.045	11.96	0.057	0.03
	$9/2^-$	$13/2^-$	4	5.831	11.368	10.96	0.027	0.300
	$9/2^-$	$11/2^+$	1	5.785	11.017	13.27	0.061	0.0015
	$9/2^-$	$15/2^-$	4	5.752	11.823	12.60	9.563×10^{-3}	0.0069
	$9/2^-$	$15/2^+$	3	5.742	11.620	13.44	0.0153	0.001
	$9/2^-$	$7/2^-$	2	5.618	12.149	11.39	4.514×10^{-3}	0.113
	$9/2^-$	$17/2^-$	4	5.668	12.316	14.12	3.073×10^{-3}	2.1×10^{-4}
	$9/2^-$	$9/2^-$	0	5.638	11.808	11.79	9.673×10^{-3}	0.044
	$9/2^-$	$7/2^+$	1	5.618	12.003	13.94	6.318×10^{-3}	3.2×10^{-4}
	$9/2^-$	$11/2^-$	2	5.568	12.452	13.55	2.247×10^{-3}	7.7×10^{-4}
	$9/2^-$	$9/2^+$	1	5.555	12.387	17.70	2.610×10^{-3}	1.5×10^{-4}
	$9/2^-$	$9/2^+$	1	5.449	13.048	10.44	5.696×10^{-4}	–
	$9/2^-$	$11/2^+$	1	5.487	12.809	14.74	9.876×10^{-4}	5×10^{-5}
	$9/2^-$	$13/2^-$	2	5.474	13.035	13.84	5.869×10^{-4}	4×10^{-4}
$^{251}\text{Cf} \to {}^{247}\text{Cm} + \alpha$	$1/2^+$	$9/2^-$	5	6.220	9.626	10.45	44.406	2.60
	$1/2^+$	$11/2^-$	5	6.158	9.948	9.77	21.156	12.5
	$1/2^+$	$13/2^-$	7	6.085	11.060	11.09	1.635	0.60
	$1/2^+$	$5/2^+$	2	5.993	10.030	9.86	17.516	27.6
	$1/2^+$	$7/2^+$	4	5.954	10.729	10.27	3.503	4
	$1/2^+$	$7/2^+$	4	5.935	10.834	10.47	2.751	2.50
	$1/2^+$	$9/2^+$	4	5.903	11.920	10.31	0.226	3.60
	$1/2^+$	$9/2^+$	4	5.874	11.875	10.97	2.503	0.80
	$1/2^+$	$1/2^+$	0	5.820	10.771	9.32	3.180	35.4
	$1/2^+$	$3/2^+$	2	5.787	11.188	10.35	1.217	3.30
	$1/2^+$	$5/2^+$	2	5.771	11.280	10.18	0.985	4.90
	$1/2^+$	$7/2^+$	4	5.703	12.159	10.87	0.132	1.0
	$1/2^+$	$3/2^+$	2	5.701	11.690	10.87	0.386	1
	$1/2^+$	$5/2^+$	2	5.638	12.065	11.44	0.162	0.27
$^{253}\text{Cf} \to {}^{249}\text{Cm} + \alpha$	$7/2^+$	$7/2^+$	0	6.121	9.182	6.72	78.479	0.29
	$7/2^+$	$9/2^+$	2	6.060	9.745	7.98	21.466	0.016

Table 3. *Continued.*

Transitions	I_i^π	I_f^π	$\ell_{\mathrm{min.}}(\hbar)$	Q (MeV)	$\log_{10}T_{1/2}$ (s)		$\mathrm{BR}_{\mathrm{cal.}}(\%)$	$\mathrm{BR}_{\mathrm{expt.}}(\%)$
					CYEM	Expt.		
$^{251}\mathrm{Fm} \to {}^{247}\mathrm{Cf} + \alpha$	$9/2^-$	$7/2^+$	1	7.470	3.941	4.28	48.268	0.027
	$9/2^-$	$9/2^+$	1	7.415	4.160	4.90	29.752	0.0167
	$9/2^-$	$11/2^+$	1	7.348	4.432	4.99	15.584	0.0052
	$9/2^-$	$13/2^+$	3	7.269	5.127	5.76	3.145	9×10^{-4}
	$9/2^-$	$5/2^+$	3	7.087	5.896	4.21	0.535	0.032
	$9/2^-$	$7/2^+$	1	7.043	5.718	4.22	0.807	0.031
	$9/2^-$	$9/2^-$	0	6.989	5.876	2.52	0.561	1.57
	$9/2^-$	$11/2^-$	2	6.938	6.332	3.77	0.196	0.086
	$9/2^-$	$11/2^+$	2	6.919	6.417	4.88	0.161	0.0068
	$9/2^-$	$13/2^-$	2	6.875	6.614	4.81	0.102	0.0079
	$9/2^-$	$13/2^+$	3	6.836	7.007	4.81	0.041	0.0079
	$9/2^-$	$7/2^-$	2	6.792	6.993	4.71	0.043	0.0101
	$9/2^-$	$9/2^-$	0	6.732	7.043	5.04	0.038	0.0047
$^{253}\mathrm{Fm} \to {}^{249}\mathrm{Cf} + \alpha$	$1/2^+$	$9/2^-$	5	7.24	5.888	5.41	24.711	0.16
	$1/2^+$	$11/2^-$	5	7.178	6.147	4.71	13.611	0.80
	$1/2^+$	$5/2^+$	2	7.095	5.674	3.91	40.449	5.1
	$1/2^+$	$7/2^+$	4	7.052	6.361	4.55	8.316	1.18
	$1/2^+$	$15/2^-$	7	7.020	7.574	5.58	0.509	0.108
	$1/2^+$	$9/2^+$	4	6.997	6.601	4.61	4.785	1.01
	$1/2^+$	$1/2^+$	0	6.823	6.646	4.17	4.314	2.8
	$1/2^+$	$3/2^+$	2	6.800	6.987	5.16	1.967	0.29
	$1/2^+$	$5/2^+$	2	6.780	7.079	5.13	0.310	0.31
	$1/2^+$	$(1/2, 3/2, 5/2)^+$	0	6.690	7.265	5.36	1.037	0.18
$^{255}\mathrm{Fm} \to {}^{251}\mathrm{Cf} + \alpha$	$7/2^+$	$1/2^+$	4	7.290	5.402	4.86	7.832	0.070
	$7/2^+$	$3/2^+$	2	7.265	4.989	4.75	20.273	0.090
	$7/2^+$	$5/2^+$	2	7.242	5.085	4.10	16.252	0.40
	$7/2^+$	$7/2^+$	0	7.184	5.085	4.01	16.252	0.5
	$7/2^+$	$7/2^+$	0	7.184	5.085	1.73	16.252	93.4
	$7/2^+$	$9/2^+$	2	7.124	5.584	3.00	5.151	5.04
	$7/2^+$	$9/2^+$	2	7.143	5.502	4.59	6.221	0.130
	$7/2^+$	$3/2^+$	2	7.112	5.635	5.36	4.581	0.022
	$7/2^+$	$5/2^+$	2	7.079	5.777	5.47	3.303	0.0170
	$7/2^+$	$7/2^+$	0	7.032	5.739	5.80	3.605	0.0080
	$7/2^+$	$13/2^+$	4	6.994	6.662	5.80	0.430	0.0080
	$7/2^+$	$9/2^+$	2	6.970	6.254	6.40	1.101	0.0020
	$7/2^+$	$13/2^+$	4	6.965	6.790	4.66	0.321	0.110
	$7/2^+$	$11/2^-$	3	6.420	9.075	5.49	1.663×10^{-3}	0.0160
	$7/2^+$	$11/2^+$	2	6.898	6.576	6.62	0.602	0.0012
	$7/2^+$	$15/2^+$	4	6.866	7.233	5.59	0.116	0.0130
	$7/2^+$	$9/2^-$	1	6.856	6.606	5.15	0.490	0.0360
	$7/2^+$	$5/2^+$	2	6.646	7.743	5.47	0.036	0.0170
	$7/2^+$	$7/2^+$	0	6.700	7.247	5.56	0.112	0.0140
	$7/2^+$	$3/2^-$	3	6.689	7.765	9.10	0.034	4×10^{-6}
	$7/2^+$	$7/2^-$	1	6.665	7.494	9.10	0.034	4×10^{-6}
	$7/2^+$	$1/2^-$	3	6.654	7.931	9.23	0.023	3×10^{-6}
	$7/2^+$	$9/2^+$	2	6.641	7.764	6.23	0.034	0.0030
	$7/2^+$	$5/2^-$	1	6.582	7.892	8.93	0.025	6×10^{-6}
	$7/2^+$	$3/2^+$	2	6.516	8.372	8.12	8.393×10^{-3}	3.8×10^{-5}
	$7/2^+$	$5/2^-$	1	6.348	9.057	8.15	1.733×10^{-3}	3.6×10^{-5}
	$7/2^+$	$9/2^+$	2	6.316	9.379	8.34	8.258×10^{-4}	2.3×10^{-5}
	$7/2^+$	$3/2^-$	3	6.308	9.645	8.09	4.476×10^{-4}	4.1×10^{-5}
	$7/2^+$	$5/2^-$	1	6.281	9.403	8.14	7.837×10^{-4}	3.7×10^{-5}
	$7/2^+$	$7/2^-$	1	6.246	9.586	8.36	5.128×10^{-4}	2.2×10^{-5}

Table 3. *Continued.*

Transitions	I_i^π	I_f^π	$\ell_{\text{min.}}(\hbar)$	Q (MeV)	$\log_{10}T_{1/2}$ (s)		BR$_{\text{cal.}}$(%)	BR$_{\text{expt.}}$(%)
					CYEM	Expt.		
	$7/2^+$	$9/2^-$	1	6.212	9.766	8.03	3.388×10^{-4}	4.7×10^{-5}
	$7/2^+$	$9/2^-$	1	6.204	9.808	8.70	3.076×10^{-4}	1×10^{-5}
	$7/2^+$	$9/2^-$	1	6.195	9.856	8.90	2.754×10^{-4}	6.3×10^{-6}
	$7/2^+$	$11/2^-$	3	6.134	10.563	9.10	5.276×10^{-5}	4×10^{-6}
	$7/2^+$	$7/2^+$	0	6.105	10.259	8.94	1.089×10^{-4}	5.8×10^{-6}
	$7/2^+$	$7/2^+$	0	6.040	10.616	8.43	4.785×10^{-5}	1.9×10^{-5}
$^{257}\text{Fm} \to {}^{253}\text{Cf} + \alpha$	$9/2^+$	$7/2^+$	2	6.910	6.603	6.94	43.71	0.58
	$9/2^+$	$9/2^+$	0	6.848	6.663	6.17	38.075	3.39
	$9/2^+$	$11/2^+$	2	6.773	7.228	6.93	10.367	0.6
	$9/2^+$	$9/2^+$	0	6.669	7.467	4.73	5.979	93.6
	$9/2^+$	$11/2^+$	2	6.589	8.100	6.40	1.392	2.00
	$9/2^+$	$13/2^+$	2	6.493	8.569	7.23	0.473	0.30
$^{257}\text{No} \to {}^{253}\text{Fm} + \alpha$	$3/2^+$	$1/2^+$	2	8.520	1.212	1.389	28.632	–
	$3/2^+$	$3/2^+$	0	8.498	1.032	2.54	43.333	14
	$3/2^+$	$3/2^+$	0	8.396	1.375	0.684	19.735	71
	$3/2^+$	$5/2^+$	2	8.361	1.747	2.30	8.354	1.7

Table 4. Logarithmic half-lives for α decay for even–even isotopes of Cm, Cf, Fm and No nuclei from the ground state to the excited states of the daughter nuclei.

Transitions	I_i^π	I_f^π	$\ell_{\text{min.}}(\hbar)$	Q (MeV)	$\log_{10}T_{1/2}$(s)		BR$_{\text{cal.}}$(%)	BR$_{\text{expt.}}$(%)
					CYEM	Expt.		
$^{238}\text{Cm} \to {}^{234}\text{Pu} + \alpha$	0^+	0^+	0	6.926	4.276	3.937	71.432	2.67
	0^+	2^+	2	6.880	4.674	4.295	28.568	1.17
$^{240}\text{Cm} \to {}^{236}\text{Pu} + \alpha$	0^+	0^+	0	6.353	6.864	6.368	69.89	70.9
	0^+	2^+	2	6.308	7.280	6.759	26.82	28.8
	0^+	4^+	4	6.206	8.210	9.504	3.151	5.184×10^{-2}
	0^+	6^+	6	6.047	9.590	10.074	0.1314	1.396×10^{-2}
$^{242}\text{Cm} \to {}^{238}\text{Pu} + \alpha$	0^+	0^+	0	6.171	7.740	7.148	70.43	74.08
	0^+	2^+	2	6.127	8.165	7.604	26.47	25.92
	0^+	4^+	4	6.025	9.118	10.474	2.949	3.50×10^{-2}
	0^+	6^+	6	5.868	10.237	11.355	0.112	4.6×10^{-3}
	0^+	8^+	8	5.657	12.387	13.716	1.587×10^{-3}	2×10^{-5}
	0^+	1^-	1	5.566	11.153	12.620	2.72×10^{-2}	2.5×10^{-4}
	0^+	3^-	3	5.510	11.806	13.918	6.050×10^{-3}	1.26×10^{-5}
	0^+	5^-	5	5.408	12.932	15.676	4.527×10^{-4}	2.2×10^{-7}
	0^+	0^+	0	5.230	13.200	14.462	2.442×10^{-4}	3.6×10^{-6}
	0^+	1^-	1	5.208	13.409	14.965	1.509×10^{-4}	1.13×10^{-6}
	0^+	2^+	2	5.188	13.670	14.788	8.275×10^{-5}	1.7×10^{-6}
	0^+	2^+	2	5.144	13.965	14.450	4.195×10^{-5}	3.7×10^{-6}
	0^+	4^+	4	5.045	15.053	15.527	3.426×10^{-6}	3.1×10^{-7}
	0^+	0^+	0	4.942	15.177	15.278	2.575×10^{-6}	5.5×10^{-7}
	0^+	2^+	2	4.907	15.628	15.302	9.115×10^{-7}	5.2×10^{-7}
$^{244}\text{Cm} \to {}^{240}\text{Pu} + \alpha$	0^+	0^+	0	5.858	9.451	8.758	71.76	76.90
	0^+	2^+	2	5.815	9.899	9.280	25.58	23.10
	0^+	4^+	4	5.716	10.900	11.334	2.552	2.04×10^{-2}
	0^+	6^+	6	5.564	12.394	12.097	0.082	3.52×10^{-3}
	0^+	8^+	8	5.361	14.342	14.042	9.225×10^{-4}	4×10^{-5}
	0^+	1^-	1	5.261	13.114	13.896	1.56×10^{-2}	5.6×10^{-5}

Table 4. *Continued.*

Transitions	I_i^π	I_f^π	$\ell_{\mathrm{min.}}(\hbar)$	Q (MeV)	$\log_{10}T_{1/2}$(s)		$\mathrm{BR}_{\mathrm{cal.}}$(%)	$\mathrm{BR}_{\mathrm{expt.}}$(%)
					CYEM	Expt.		
	0^+	3^-	3	5.209	13.783	15.040	3.341×10^{-5}	4×10^{-6}
	0^+	0^+	0	4.997	14.835	13.471	2.964×10^{-6}	1.49×10^{-4}
	0^+	2^+	2	4.958	15.321	13.945	9.68×10^{-5}	5×10^{-5}
$^{246}\mathrm{Cm} \rightarrow {}^{242}\mathrm{Pu} + \alpha$	0^+	0^+	0	5.431	11.986	11.178	75.59	82.2
	0^+	2^+	2	5.387	12.477	11.842	24.41	17.8
$^{248}\mathrm{Cm} \rightarrow {}^{244}\mathrm{Pu} + \alpha$	0^+	0^+	0	5.117	14.056	13.04	75.81	75
	0^+	2^+	2	5.073	14.577	13.697	22.84	16.52
	0^+	4^+	4	4.962	15.814	16.069	1.323	7×10^{-2}
	0^+	6^+	6	4.799	17.633	17.216	0.020	5×10^{-3}
$^{244}\mathrm{Cf} \rightarrow {}^{240}\mathrm{Cm} + \alpha$	0^+	0^+	0	7.284	3.678	3.066	70.19	53
	0^+	2^+	2	7.246	4.050	3.535	29.81	18
$^{246}\mathrm{Cf} \rightarrow {}^{242}\mathrm{Cm} + \alpha$	0^+	0^+	0	6.817	5.690	5.109	69.44	79.3
	0^+	2^+	2	6.775	6.100	5.694	27.015	20.6
	0^+	4^+	4	6.680	7.001	7.832	3.393	0.150
	0^+	6^+	6	6.529	8.345	8.804	0.154	1.6×10^{-2}
$^{248}\mathrm{Cf} \rightarrow {}^{244}\mathrm{Cm} + \alpha$	0^+	0^+	0	6.316	8.095	7.460	71.49	80
	0^+	2^+	2	6.213	8.537	8.071	25.84	19.6
	0^+	4^+	4	6.174	9.524	9.761	2.66	0.40
$^{250}\mathrm{Cf} \rightarrow {}^{246}\mathrm{Cm} + \alpha$	0^+	0^+	0	6.083	9.333	8.615	69.24	82.58
	0^+	2^+	2	6.040	9.793	9.299	23.84	17.11
	0^+	4^+	4	5.941	10.335	11.080	6.845	0.283
	0^+	6^+	6	5.790	12.335	12.687	6.85×10^{-2}	7×10^{-3}
$^{252}\mathrm{Cf} \rightarrow {}^{248}\mathrm{Cm} + \alpha$	0^+	0^+	0	6.172	8.892	7.921	72.218	81.5
	0^+	2^+	2	6.129	9.356	8.671	24.84	14.5
	0^+	4^+	4	6.028	10.391	10.452	2.818	0.24
	0^+	6^+	6	5.874	11.925	12.547	6.69×10^{-2}	1.93×10^{-3}
	0^+	8^+	8	5.667	13.014	14.069	6.87×10^{-4}	5.8×10^{-5}
$^{246}\mathrm{Fm} \rightarrow {}^{242}\mathrm{Cf} + \alpha$	0^+	0^+	0	8.330	0.625	0.17	69.854	74
	0^+	2^+	2	8.285	0.990	0.784	30.144	18
$^{248}\mathrm{Fm} \rightarrow {}^{244}\mathrm{Cf} + \alpha$	0^+	0^+	0	7.948	1.988	1.556	70.15	74
	0^+	2^+	2	7.907	2.359	2.156	29.85	18.6
$^{250}\mathrm{Fm} \rightarrow {}^{246}\mathrm{Cf} + \alpha$	0^+	0^+	0	7.509	3.664	3.255	71.52	75
	0^+	2^+	2	7.465	4.064	3.954	28.47	15
$^{252}\mathrm{Fm} \rightarrow {}^{248}\mathrm{Cf} + \alpha$	0^+	0^+	0	7.106	5.349	5.04	69.48	84
	0^+	2^+	2	7.065	5.759	5.79	27.03	15
	0^+	4^+	4	6.968	6.668	6.98	3.33	0.97
	0^+	6^+	6	6.821	7.993	8.603	0.158	2.3×10^{-2}
$^{254}\mathrm{Fm} \rightarrow {}^{250}\mathrm{Cf} + \alpha$	0^+	0^+	0	7.260	4.721	4.067	69.79	84.9
	0^+	2^+	2	7.217	5.136	4.843	26.84	14.2
	0^+	4^+	4	7.118	6.057	6.082	3.219	0.82
	0^+	6^+	6	6.964	7.410	8.176	0.143	6.6×10^{-3}
$^{256}\mathrm{Fm} \rightarrow {}^{252}\mathrm{Cf} + \alpha$	0^+	0^+	0	6.980	6.014	5.14	73.9	6.9
	0^+	2^+	2	6.934	6.466	5.89	26.01	1.22
$^{252}\mathrm{No} \rightarrow {}^{248}\mathrm{Fm} + \alpha$	0^+	0^+	0	8.499	0.937	0.74	70.77	51
	0^+	2^+	2	8.455	1.321	1.217	29.23	17
$^{254}\mathrm{No} \rightarrow {}^{250}\mathrm{Fm} + \alpha$	0^+	0^+	0	8.179	2.057	1.82	68.17	84.9
	0^+	2^+	2	8.136	2.447	2.596	27.78	14.2
	0^+	4^+	4	8.037	3.307	3.835	3.834	0.82
	0^+	6^+	6	7.883	4.559	5.929	0.215	6.6×10^{-3}
$^{256}\mathrm{No} \rightarrow {}^{252}\mathrm{Fm} + \alpha$	0^+	0^+	0	8.533	0.873	0.53	71.57	86.6
	0^+	2^+	2	8.487	1.274	1.357	28.43	12.9

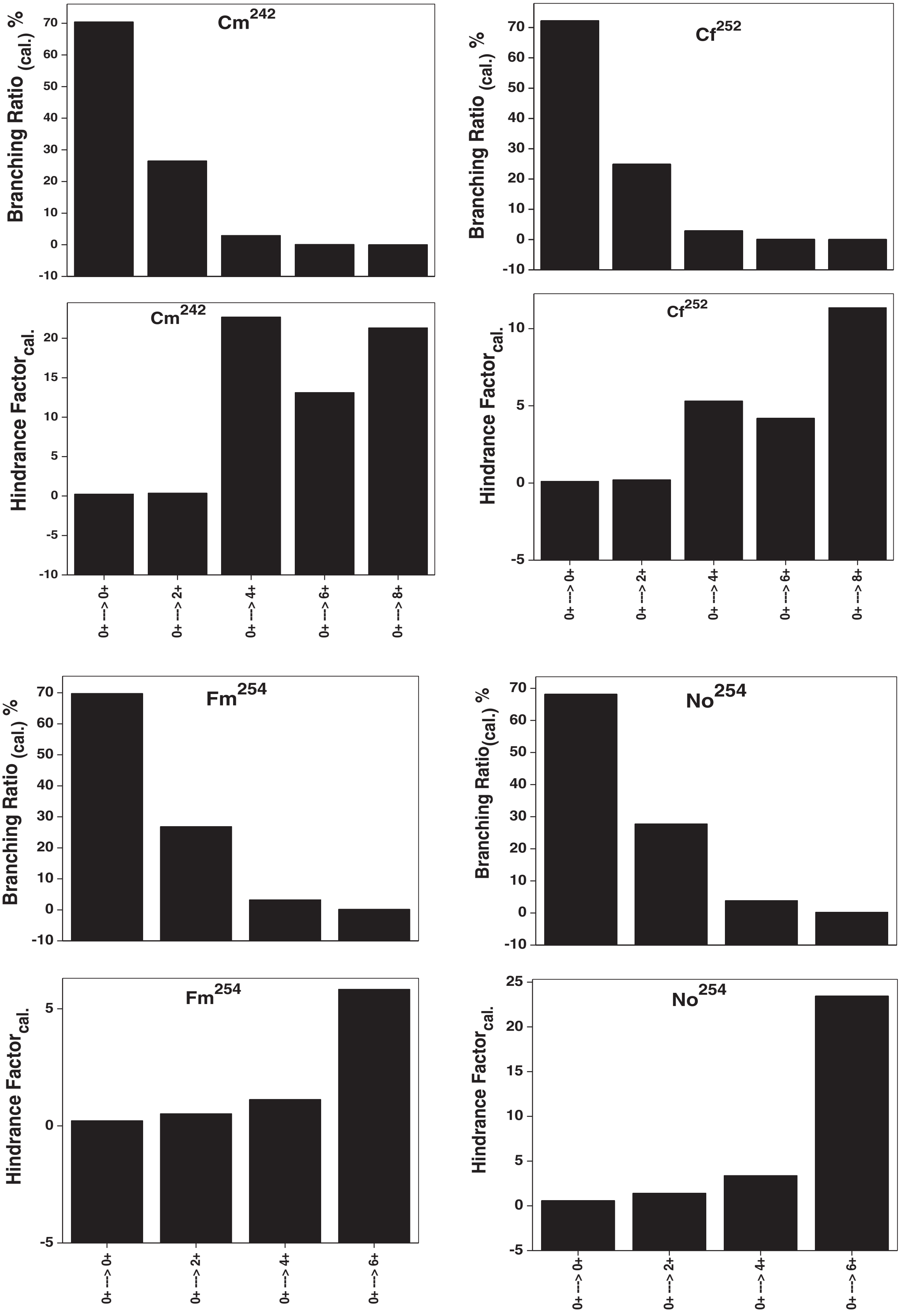

Figure 5. Histogram for branching ratio and hindrance factor of even–even isotopes of Cm, Cf, Fm and No nuclei.

The estimated standard deviation for the half-lives of nuclei for the transition from the ground state of the parent nuclei to ground state of the daughter nuclei by our model is 1.336.

4. Conclusions

In this paper, we have presented a detailed study of the fine structure in the α decay of even–even and even–odd isotopes of Cm, Cf, Fm and No nuclei. The α decay half-lives of even–odd and even–even nuclei from the ground state of the parent nuclei to the ground state of the daughter nuclei and the ground state to an excited state of the daughter nuclei have been calculated using the CYEM. Our results are consistent with theoretical values and experimental data. By including centrifugal potential term, the half-life value is found to be increasing, because it increases the thickness and height of the barrier. In even–even nuclei, the branching ratio is found to be decreasing from the second excited states of the daughter nuclei, which shows that α transitions to those excited states are strongly hindered. The intensity of α transition is the maximum for the transition from the ground state of the parent nuclei to the ground state of the daughter nuclei. But in most decays of the even–odd nuclei, the branching ratios to the excited states are larger than the value to the ground state of the daughter nuclei, as the parent and the corresponding excited daughter nuclei have the same internal structure and also due to the odd parity effect.

References

[1] G Gamow, *Nature* **126**, 397 (1930)
[2] S Rosenblum, *C. R. Acad. Sci. Paris* **188**, 1401 (1929)
[3] D S Delion and J Suhonen, *Phys. Rev. C* **64**(**6**), 064302 (2001)
[4] N Bijnens *et al*, **1995**, 110 (2007)
[5] D P Delion *et al*, *J. Phys. G* **43**(**9**), 095109 (2016)
[6] M Mirea, *Phys. Rev. C* **96**(**6**), 064607 (2017)
[7] K P Santhosh *et al*, *J. Phys. G* **38** (**7**), 075101 (2011)
[8] K P Santhosh, S Sahadevan and J G Joseph, *Nucl. Phys. A* **850**(**1**), 34 (2011)
[9] A Adel and T Alharbi, *Nucl. Phys. A* **975**, 1 (2018)
[10] K P Santhosh, J George Joseph and B Priyanka, *Nucl. Phys. A* **877(1)**, 1 (2012)
[11] V Y Denisov and A A Khudenko, *Phys. Rev. C* **80**(**3**), 034603 (2009)
[12] Y Z Wang *et al*, *Phys. Rev. C* **79**(**1**), 014316 (2009)
[13] N Dongdong and R Zhongzhou, *J. Phys. G: Nucl. Phys.* **37**(**3**), 035104 (2010)
[14] D Ni and Z Ren, *Phys. Rev. C* **83**(**6**), 067302 (2011)
[15] K P Santhosh and C Nithya, *Pramana – J. Phys.* **90**(**3**): 35 (2018)
[16] G Shanmugam, G M Carmel Vigila Bai and B Kamalaharan, *Phys. Rev. C* **51**(**5**), 2616 (1995)
[17] G M Carmel Vigila Bai and R Nithya Agnes, *Proceedings of Department of Atomic Energy (DAE), Symposium on Nuclear Physics* (Prasanthi Nilayam, Andhra Pradesh, India, 2015) Vol. 60, p. 304
[18] G M Carmel Vigila Bai and R Nithya Agnes, *Int. J. Curr. Sci. Res.* **2**(**3**), 447 (2016)
[19] G M Carmel Vigila Bai and R Nithya Agnes, *J. Appl. Sci. Eng. Methodol.* **2**(**3**), 363 (2016)
[20] G M Carmel Vigila Bai and R Nithya Agnes, *Proceedings of Department of Atomic Energy (DAE) Symposium on Nuclear Physics* (Kolkatta, India, 2016) Vol. 61, p. 338
[21] G M Carmel Vigila Bai and R Nithya Agnes, *Pramana – J. Phys.* **88**: 43 (2017)
[22] G A Pik-Pichak, *Yad. Fiz.* **44**(**6**), 1421 (1986)
[23] H J Krappe, J R Nix and A J Sierk, *Phys. Rev. C* **20**(**3**), 992 (1979)
[24] http://www.nndc.bnl.gov
[25] G Audi, A H Wapstra and C Thibault, *Nucl. Phys. A* **729**(**1**), 337 (2003)
[26] K N Huang *et al*, *At. Data Nucl. Data Tables* **18(3)**, 243 (1976)
[27] J R Nix, *Ann. Phys.* **41**, 52 (1967)
[28] R Hofstadeter, *Nuclear radii. Nuclear physics and technology* edited by H Schopper (Springer-Verlag, Berlin, 1967) Vol. 2
[29] H G de Carvalho, J B Martins and O A P Tavares, *Phys. Rev. C* **34**(**6**), 2261 (1986)
[30] P Möller *et al*, *At. Data Nucl. Data Tables* **109–110**, 1 (2016)
[31] P Moeller, J R Nix and K L Kratz, *At. Data Nucl. Data Tables* **66(2)**, 131 (1997)
[32] V Y Denisov and A A Khudenko, *At. Data Nucl. Data Tables* **95**(**6**), 815 (2009)
[33] D N Poenaru *et al*, *Phys. Rev. C* **32**(**2**), 572 (1985)
[34] C Xu and Z Ren, *Phys. Rev. C* **73**(**4**), 041301 (2006)